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Research Article

Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects

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The use of conventional manufacturing methods is mainly limited by the size of the production run and the geometrical complexity of the component, and as a result we are occasionally forced to use processes and tools that increase the final cost of the element being produced. Additive manufacturing techniques provide major competitive advantages due to the fact that they adapt to the geometrical complexity and customised design of the part to be manufactured. The following may also be achieved according to field of application: lighter weight products, multimaterial products, ergonomic products, efficient short production runs, fewer assembly errors and, therefore, lower associated costs, lower tool investment costs, a combination of different manufacturing processes, an optimised use of materials, and a more sustainable manufacturing process. Additive manufacturing is seen as being one of the major revolutionary industrial processes of the next few years. Additive manufacturing has several alternatives ranging from simple RepRap machines to complex fused metal deposition systems. This paper will expand upon the structural design of the machines, their history, classification, the alternatives existing today, materials used and their characteristics, the technology limitations, and also the prospects that are opening up for different technologies both in the professional field of innovation and the academic field of research. It is important to say that the choice of technology is directly dependent on the particular application being planned: first the application and then the technology.

1. Historical and Current Framework

Many different additive manufacturing (AM) technologies enable the production of prototypes and fully functional artefacts. Although very different in solution, principle, and embodiment, significant functional commonality exists among the technologies.

In order to enter the subject from its origins, before proposing a classification or analyzing the different technologies and their advantages and disadvantages, a chronological analysis of facts will be carried out that will allow us to later base the conclusions. This chronological analysis will be based on dates of publication of works, dates of application for patents, and dates of acceptance of these patents, being aware that in any case the dates in which the developments were reached are always prior to those dates of a public nature.

Without a doubt, the milestone that marked the beginning of additive manufacturing took place on 9th March **1983**, when Charles W. Hull successfully printed a teacup on the first additive manufacturing system: the stereolithography apparatus SLA-1, which he himself built [1].

From then on, there were several advances that paved the way for what is today known as additive manufacturing (Table 1). From a chronological point of view, the most relevant are as follows [2]:

> **1986**. Carl R. Deckard, at the University of Texas, develops a "method and apparatus for producing parts by selective sintering", a first step in the development of additive manufacturing by means of selective sintering (SS).
>
> **1988**. Michael Feygin and his team at Helisys, Inc. develop a method for "forming integral objects from

Table 1: Key inventions in additive manufacturing (ordered by publication of patent).

Technology	Inventors	Patent	Development centre	Request for patent	Publication of patent	Principle of operation
Stereolithography SL	Charles W. Hull	Method and apparatus for production of three-dimensional objects by stereolithography	3D Systems	08.08.1984	12.02.1986	Photopolymerization of a photosensitive resin using UV light
Selective Sintering SS	Carl R. Deckard	Method and apparatus for producing parts by selective sintering	University of Texas	17.10.1986	21.04.1988	Selective sintering of powder (fusion – solidification using laser)
Material Deposition MD	Scott S. Crump	Apparatus and method for creating three-dimensional objects	Stratasys, Inc.	30.10.1989	01.05.1991	Deposition of material, using a nozzle, in plastic state (heated by electrical resistance)
Jet Prototyping (injection) JP	Emanuel M. Sachs; John S. Haggerty; Michael J. Cima; Paul A. Williams	Three-dimensional printing techniques	Massachusetts Inst. Technology	08.12.1989	09.06.1991	Injection of binding agent and coloured ink on a bed of powdered material
Laminated Manufacturing (cutting) LM	Feygin, Michael; Pak, Sung Sik	Forming integral objects from laminations - Apparatus for forming an integral object from laminations	Helisys, Inc.	05.10.1988	18.04.1996	Cutting and gluing of laminations with the geometry determined for each layer

Source: World Intellectual Property Organization (WIPO), https://patentscope.wipo.int.

laminations", an automatic lamination cutting system (laminated manufacturing - LM) that produces layers with the dimensions marked out by the electronic file, layers which will then be bonded to form the final prototype.

1989. Scott S. Crump, at the company Stratasys, Inc., develops an "apparatus and method for creating three-dimensional objects", a first step in the development of additive manufacturing by means of fused deposition modelling (FDM).

1989. Emanuel M. Sachs and his team, at Massachusetts Inst. Technology, develop "three-dimensional printing techniques", a process of injecting binding agent and coloured ink on a bed of powdered material, using the injectors of a conventional ink-jet printer to do so.

As an evolution of Hull's work based on photopolymerization, other processes have been developed:

(i) Solid Creation System (SCS). Developed by Sony Corporation, JSR Corporation and D-MEC Corporation in 1990.

(ii) Solid Object Ultraviolet Laser Printer (SOUP) Developed by CMET Inc. in 1990.

(iii) Solid Ground Curing (SGC) developed by Cubital Ltd. in 1991

(iv) Inkjet Rapid Prototyping (IRP), the parts are formed by injecting a photopolymer drop by drop which is then cured using ultraviolet light. Developed by Object Geometries Ltd. in 2000, under the name Polyjet.

As an evolution of Deckard's work based on sintering, other processes have been developed [3]:

(i) Direct metal laser sintering (DMLS), where the base material is metal powder and the grains are bonded by sintering, without the grains being fully fused together.

(ii) Selective laser melting (SLM), where metal powder is fully fused together and so the process is not sintering but rather melting.

As an evolution of Crump's work on fused deposition modeling, other processes have been developed:

(i) Metal deposition (MD), where a metal filler material (powder jet or wire) is deposited by a nozzle following the path marked out by the G-code in the .stl or .amf file [4].

(ii) Fused Filament Fabrication (FFF), name from the RepRap community, an open community at RepRap.org, founded by Adrian Bowyer at the University of Bath in 2004 [5].

At this point, hardfacing processes using numerical control (NC) should be mentioned, which are predecessors of fused deposition modeling and prior to the work of Crump, with the difference being that they were not based on electronic files generated by means of solid modeling systems [4]. Although additive manufacturing could date back to automated welding systems (1970s), where a robotic arm controlled by numerical control (G-code) deposited material in welding or hardfacing operations (which may be a similar case), it was not until 1983 that this G-code was used to control a laser that "solidifies" a resin and builds a part using a virtual model (solid model and .stl file).

As an evolution of the work of Sachs and his team on the injection of binding agent or base material, other processes have been developed:

(i) MultiJet Modeling System (MJM) developed by 3D Systems Inc. in 1999, with multiple heads in parallel that move along one axis.

(ii) ModelMaker and Pattern Master, by Solidscape, with one single print head that moves along two axes.

(iii) ProMetal, division of Extrude Hone Corporation, process that binds together steel powder and then infiltrates molten bronze to produce a part that is 40% steel and 60% bronze [6].

Finally, as an evolution of the work of Feygin and his team based on cutting laminations, other processes have been developed:

(i) Selective Deposition Lamination (SDL) Invented in 2003 by MacCormack. The SDL technique works by depositing an adhesive in the area required, both the model and the support, and a blade that cuts the outline of the layer [7].

It is interesting to point out that there are current processes based on more than one of the contributions stated or on integrated processes. This is the case of polyjet modeling (PJM), which is said to be a combination of stereolithography and injection.

Nowadays, the volume of processes, technologies and initialisms is so high that there is no extensive classification system in operation. In Table 2 we can see a list of initialisms used in this field, which is by no means exhaustive, which gives us an idea of how technology is evolving.

In order to highlight the basic pillars of additive manufacturing in Table 2, the abbreviations referring to the technologies discussed at the beginning of this introduction have been highlighted in italic.

Given the large number of initiatives and processes that are developed and patented every day, there is no doubt that additive manufacturing is a technology that will set the standards for many productive processes in the short and medium term. One more proof of this is that the European Union has decided that manufacturing in general and additive manufacturing in particular shall be one of the key tools to tackle some of the European challenges and their subsequent objectives, above all economic growth and the creation of added value and high-quality jobs. This decision is generating the setting up of research and innovation support and promotion programmes aimed at achieving a situation in

Table 2: A sea of initialisms.

3DB	three-dimensional bioplotter	LPD	laser powder deposition
3DP	three-dimensional printing	LPF	laser powder fusion
AF	additive fabrication	LPS	liquid-phase sintering
ALPD	automated laser powder deposition	LRF	laser rapid forming
AM	*additive manufacturing*	LS	laser sintering
BM	biomanufacturing	M^3D	maskless mesoscale material deposition
CAM-LEM	computer-aided manufacturing of laminated engineering materials	MD	metal deposition
DCM	direct composite manufacturing	*MD*	*material deposition*
DIPC	direct inkjet printing of ceramics	MEM	melted extrusion manufacturing
DLC	direct laser casting	MIM	material increase manufacturing
DLF	directed light fabrication	MJM	multijet modeling system
DLP	digital light processing	MJS	multiphase jet solidification
DMD	direct metal deposition	MS	mask sintering
DMLS	direct metal laser sintering	M-SL	microstereolithography
EBM	electron beam melting	PBF	powder bed fusion
EBW	electron beam welding	PJM	poly jet modeling
EP	electrophotographic printing	RFP	rapid freeze prototyping
ERP	electrophotographic rapid printing	RM	rapid manufacturing
FDC	fused deposition of ceramics	RP	rapid prototyping
FDM	fused deposition modeling	RPM	rapid prototyping and manufacturing
FFEF	freeze-form extrusion fabrication	RT	rapid tooling
FFF	fused filament fabrication	RTM	rapid tool maker
FLM	fused layer modeling	SALDVI	selective area laser deposition and vapor infiltration
FLM	fused layer manufacturing	SCS	solid creation system
HSS	high speed sintering	SDL	selective deposition lamination
IJP-A	aqueous direct inkjet printing	SDM	shape deposition manufacturing
IJP-UV	UV direct inkjet printing	SFC	solid film curing
IJP-W	hot-melt direct inkjet printing	SFF	solid free-form fabrication
IRP	inkjet rapid prototyping	SGC	solid ground curing
JP	*jet prototyping*	SHS	selective heat sintering
LAM	laser additive manufacturing	*SL*	*stereolithography*
LC	laser cladding	SLA	stereolithography apparatus
LCVD	laser chemical vapor deposition	SL-C	stereolithography of ceramics
LDC	laser direct casting	SLM	selective laser melting
LDM	low-temperature deposition manufacturing	SLP	solid laser diode plotter
LENS	laser engineered net shaping	SLS	selective laser sintering
LFFF	laser free form fabrication	SLSM	selective laser sintering of metals
LLM	layer laminated manufacturing	SOUP	solid object ultra-violet laser printer
LM	*laminated manufacturing*	*SS*	*selective sintering*
LMD	laser material deposition	SSM-SFF	semisolid metal solid freeform fabrication
LMF	laser metal forming	SSS	solid-state sintering
LOM	layered object manufacturing	UC	ultrasonic consolidation
LOM	laminated object manufacturing	UOC	ultrasonic object consolidation

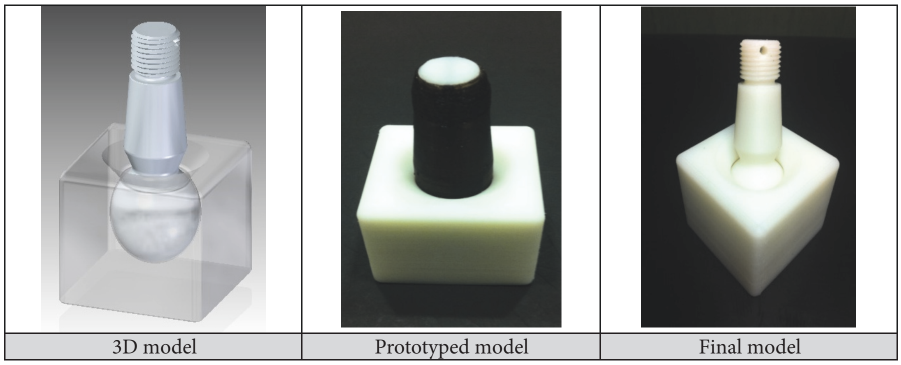


Figure 1: Ball joint mounted in its housing [8].

which additive manufacturing enables the provision of both high-value products and competitive services.

All over the world the additive manufacturing industry is beginning to respond to global, national, and regional standardisation needs via a series of working groups in which the European Union is a key participant: the ISO/TC 261, Additive manufacturing; the ASTM Committee F42 on Additive Manufacturing Technologies; the CEN/TC 438, additive manufacturing; or the AEN/CTN 116, Sistemas industriales automatizados (https://www.aenor.com/) [9].

The ISO standard (ISO 52900) defines additive fabrication as follows [9, 13]:

> "Manufacturing processes which employ an additive technique whereby successive layers or units are built up to form a model."

The terms habitually used in conjunction with additive manufacturing have been evolving at the same pace as the technological developments, and it is convenient to establish a framework of reference that enables an analysis to be carried out of the developments made and of the standardisation required for the future [14]:

(i) "*Desktop manufacturing*", perhaps the first name, in line with the names at the time (1980s) such as desktop computer, desktop design.

(ii) *"Rapid Prototyping"*. This was the first term used to describe the creation of 3D objects by way of the layer-upon-layer method. The technologies that currently exist enable the manufacture of objects that can be considered as being somewhat more than "prototypes".

(iii) *"Rapid tooling". When it became clear that the additive manufacturing system not only enabled us to build prototypes, but also moulds, matrices and tools, this name began to be used to differentiate it from rapid prototyping.*

(iv) *"3D Printing"*. This is the most commonly used term. The term "low-cost 3D printing" is frequently coined when we use printers that domestic or semi-professional users can afford.

(v) *"Freeform Fabrication"*. Is a collection of manufacturing technologies with which parts can be created without the need for part-specific tooling. A computerized model of the part is designed. It is sliced computationally, and layer information is sent to a fabricator that reproduces the layer in a real material.

(vi) *"Additive Manufacturing"*. This is the most recent term applied and it is used to describe the technology in general. It is commonly used when referring to industrial component manufacturing applications and high-performance professional and industrial equipment.

An evolution can be seen in this sequence from obtaining prototypes (with purely aesthetic and geometric goals at the beginning) to simple functional parts, tools, and moulds, to obtain complex functional parts such as those currently obtained via additive manufacturing in the metal industry.

The difference between these techniques is reduced to the application for which the additive manufacturing technology is used. This means that a rapid prototyping technique can be used as a possible technology for the rapid manufacturing of elements, tools, or moulds. It answers the following questions: how would it be possible to manufacture a ball joint fully mounted in its housing without having to manufacture the elements separately prior to their assembly? And is the mass or individual production of this unit possible at an affordable price (Figure 1)?

A characteristic common to the different additive manufacturing techniques is that of the need for a minimum number of phases in the manufacturing process starting with the development of the "idea" by the designer through to obtaining the finished product [15] (Figure 2).

Obviously, the scheme proposed by Yan and his team is a generalization since not in all AM processes G-Codes are created, and preprocessing is not contemplated (necessary in some processes).

In the process described above the designer can perform the entire product manufacturing operation from start to finish. The involvement of another technician is not necessary for carrying out any complementary operations. However, it must be taken into account that, during the process and prior to manufacture, the designer must know the determining

Detailed process of a model	Conceptual process
1. Conceptual development of the idea. 2. Design of the model in a 3D CAD application. 3. Generation of an .stl or .amf file to enable the additive manufacturing equipment to interpret the geometrical information (triangulation) modelled in CAD. 4. Orientation within the machine and generation of the NC code (G code) by the additive manufacturing equipment. 5. Manufacturing of the component. 6. Cleaning. Removal of the support material (if the technology uses support material and the component so requires). 7. Post-process phase: (improving the finish and hardening. Some technologies do not require this).	• Conceptual development 1 • 3D CAD application 2 • Generation the .stl file 3 • Generation the G code 4 • Manufacturing 5 • Cleaning 6 • Post-processing 7

Figure 2: Phases of the additive manufacturing process.

factors of the end product in order to be able to select the most suitable manufacturing technique, make the necessary modifications to the geometrical data file (stl or amf file), and review the NC code. The designer must, therefore, have a full overview of and the necessary training in all of the phases of the process [19, 20].

This article contains a full and up-to-date description of the benefits and drawbacks of the most important manufacturing methodologies and processes that exist within the scope of the additive manufacturing concept, of the characteristics of the models manufactured and their associated costs, of the functional models, the applications, and the sectors of influence. At the end, there is a reference to the RepRap community and free software due the importance they acquired last years.

It is important to establish the variables that currently support the implementation of additive manufacturing and its relation to the basic principles of each technology, which allow detecting the advantages and limitations of each of them. In Figure 3, the relationship between the main variables that intervene in the development of additive manufacturing is shown: technologies, materials, type of models, associated costs, and visual appearance. The current scope of these variables and their evolution can be seen in the subdivision that is presented in a circular diagram.

2. Processes

2.1. Additive Manufacturing Technologies. Conventional component manufacturing processes are based on the use of high-capacity resources combined with control elements to achieve extremely high levels of precision and reliability. The use of computer systems during the design engineering, manufacturing, and simulation phases of a product in combination with other techniques based on mechatronics have succeeded in making production systems highly efficient.

However, a number of limitations still plague manufacturing processes. This is because on occasion we find ourselves being forced to use processes and tools that increase the end cost of the element in accordance with the size of the production run and the geometrical complexity of the component.

Transformation processes currently exist that enable us to extract, shape, fuse, and bind the base material of our component, and for the last few years we have also been able to deposit the material where it is needed; in other words, using a virtual 3D model it is possible to manufacture the component by adding the material in accordance with the solid volume designed into the model.

Current additive-type technologies are based on the dispersion-accumulation principle (Figure 4). The material or additives filler processes are those that involve the solidification of a material the original state of which is solid, liquid, or powder by way of the production of successive layers within a predetermined space using electronic processes [21]. These methods are also known by the acronym MIM (Material Increase Manufacturing).

If we focus our attention on the application of the different manufacturing technologies used for obtaining rapid prototypes, the current technologies can be classified as additive (stereolithography, laser sintering, fused deposition modelling, etc.) and nonadditive (incremental forming, high-speed machining, pressure injection moulding, lost wax, laminating and contouring, etc.).

In Tables 3–8 the most relevant data with respect to the main additive manufacturing technologies are analysed [6, 8, 11, 21, 22].

2.2. Classification. The classification of the additive manufacturing processes has been a controversial issue, even bordering on obsession, since the appearance of the first alternatives for obtaining pieces in these technologies. The first classifications took into account whether the starting material was solid, liquid, or powder, posing inconsequential doubts that contributed little to the academic community. The same problem was found in the professional field when the first commercial solutions began to appear, since the

Figure 3: Table of contents.

classifications that were proposed had little or no utility [14, 23–25].

One of the pioneers in the classification of processes, hierarchizing them based on the starting material, is JP Kruth [26], who proposed an interesting classification in 1991. In the literature we can also find other classification alternatives based on the equipment used [27], to the process itself [28] or to the transformation of materials [29]

The classification proposed by Williams and his team [30] is very academic, but of little use from a practical point of view. However, the classification proposed by ASTM has some loopholes and disadvantages, and the same is the case with the classification proposed by ISO.

ASTM (ASTM F2792) also proposes the following groups: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [31].

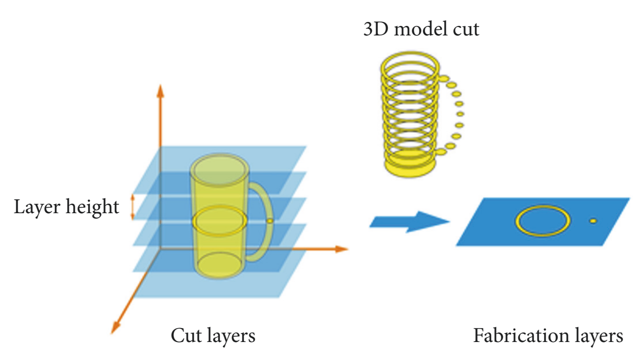


Figure 4: The dispersion-accumulation principle [8].

However, for example, it is not very coherent to separate the photopolymerization processes depending on whether they are carried out in a vat or with another alternative, such

Table 3: Stereolithography (SL).

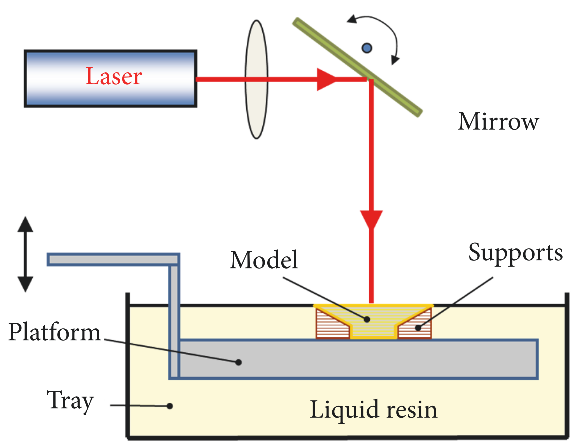
Resin Solidification - Stereolithography	
	The material undergoes point-to-point solidification due to the photopolymerisation laser being directed onto a 2D cross-section of the model (XY plane). The platform gradually descends (Z plane) in accordance with the height of the layer defined [10]. Layer thickness varies from between 0.1 and 0.2 mm. The precision in SL is +/- 0.2% (min. +/- 0.2 mm). Maximum model size: 2100x700x800 mm. The following materials can be used (epoxy-acrylic resins: Poly1500, PP, TuskXC2700T / Tusk2700W, Tusk SolidGrey3000, Flex70B, NeXt, Protogen White, Xtreme, WaterClear [11]. The properties of the material NeXt are: tensile modulus: 2370-2490 Mpa; tensile strength: 31-35 Mpa; elongation at rupture: 8-10%; flexural modulus: 2415-2525 Mpa; bending strength: 68-71 Mpa; impact strength: 47-52 J/m; deformation under load temperature: 48-57°C. Advantages and disadvantages The quality and surface finish are good or very good. Great precisions and transparent parts can be obtained. The equipment and materials are medium-high cost. They have problems to obtain pieces with cantilevers or internal holes due to the difficulty of removing the supports.

Table 4: Selective sintering/melting (SS).

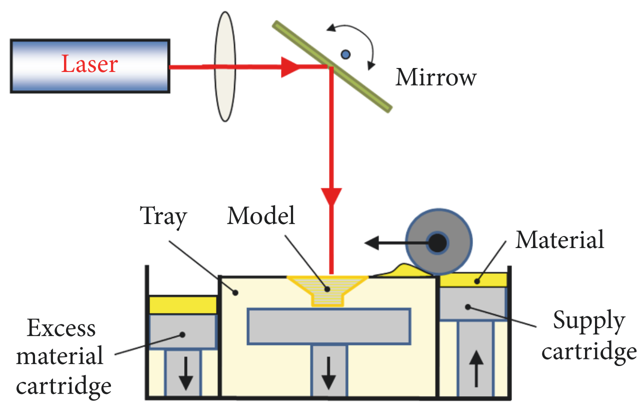
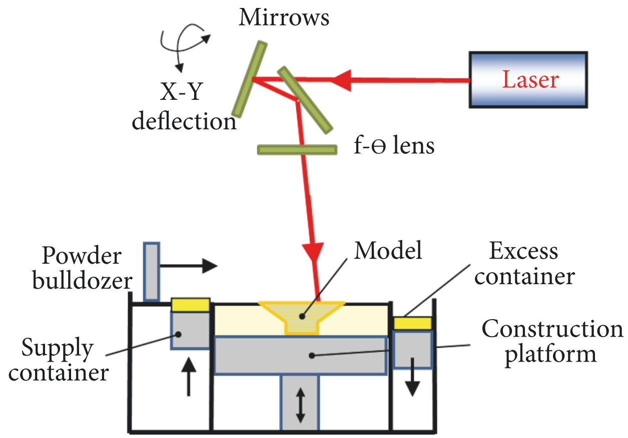
Selective Laser Sintering	
	A layer of powder is laid down and a CO_2 laser sinters it at the points selected on a 2D cross section of the model (XY plane). The platform gradually descends (Z plane) in accordance with the height of the layer defined [12]. Precision is between +/- 0.3% (min. +/- 0.3 mm). The minimum layer thickness is 0.08 mm. Maximum model size 700x380x580 mm. The following materials can be used: Polyamide (PA), Glass filled polyamide (PA-GF), Alumide, PA 2241 FR, TPU 92A-1. Properties of the PA material: tensile modulus: 1650 Mpa; tensile strength: 22 Mpa; elongation at rupture: 20%; flexural modulus: 1500 Mpa; bending strength: - Mpa; impact strength: 53 J/m; deformation under load temperature: 86°C. Advantages and disadvantages Pieces of high quality and precision are obtained. A large quantity of sintering materials is available. They do not present problems to obtain pieces with cantilevers or internal holes because the own dust makes of support. The equipment and materials are medium-high cost.
Selective Laser Melting	
	The print nozzle head is fitted with a CO_2 laser that is directed via a set of lenses onto the powdered material. The support structures are made of the same material as the model and must undergo a subsequent finishing or even machining process [3]. The minimum layer thickness is 0.020 mm. The material can be: stainless steel, Co-Cr, Inconel 625-718, titanium Ti64. Properties of the material Co-Cr: ultimate creep (R_m): 1050 Mpa; elongation (E): 14%; Young's modulus: 20 Gpa; Hardness 360 HV. Advantages and disadvantages Pieces of high quality and precision are obtained. There is a large amount of metallic materials to be sintered. Equipment and materials are expensive. They have problems to obtain pieces with cantilevers or internal holes due to the relative difficulty of removing the supports.

Table 5: Material deposition (MD).

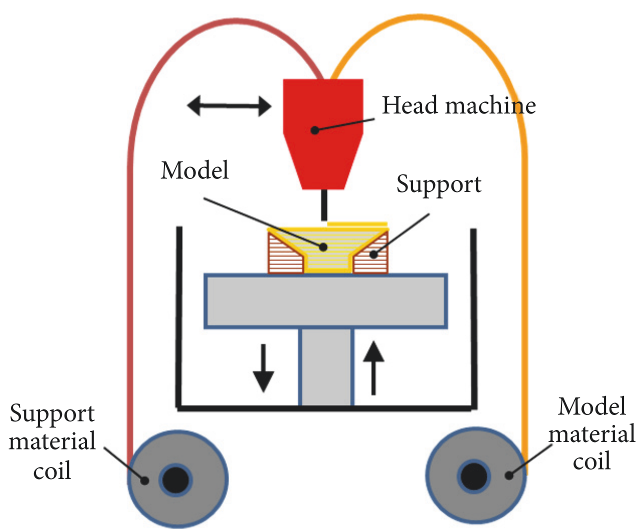
Fused Deposition Modelling	
	The wire is rolled around a coil and deposited using the thermal nozzle head that moves in accordance with the plane (XY). The platform gradually descends (Z plane) in accordance with the height of the layer defined [16]. The layer thickness is: 0.13 - 0.25mm (for ABS); 0.18 - 0.25 mm (for ABSi); 0.18 - 0.25 mm (for PC); 0.25 mm (for PPSU). The maximum model size is 914x610x914 mm. The following thermoplastic materials can be used: ABS, ABSi, ABS-M30, ABS-ESD7, PC-ABS, PC-ISO and ULTEM 9085. The properties of ABS are: tensile modulus: 1627 Mpa; tensile strength: 22 Mpa; elongation at rupture: 6%; flexural modulus: 1834 Mpa; bending strength: 41 Mpa; impact strength: 107 J/m; deformation under load temperature: 76-90°C. Advantages and disadvantages Low medium cost equipment, available even in domestic environments. Possibility of eliminating supports by dissolution and obtaining very clean pieces. Pieces of quality and precision can be obtained but resorting to high cost equipment.

Table 6: Jet prototyping (JP).

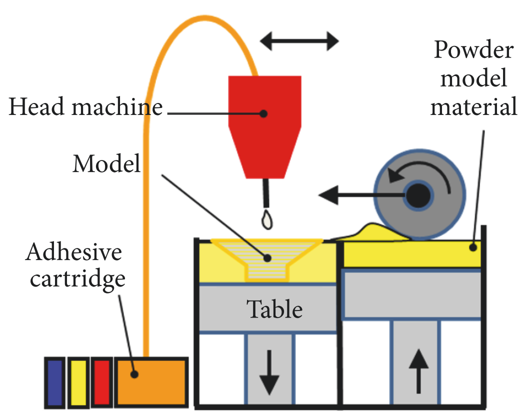
Three Dimensional Printing – Glue Injection	
	The model is built on a bed full of powdered model material. A nozzle head injects an agglutinate onto the surface of the bed and fuses the powder in accordance with the geometry of the 2D cross-section of the model. The powder is added and levelled using a roller. Once the process has been completed, the excess powder is sucked off the bed leaving the model clean. The model then has to be cured (hardened) using different coatings [17]. Minimum layer thickness is between 0.013 and 0.076 mm. The material used can be ceramic, metal and polymers. The properties of the material zp150-Z-Bond are: tensile modulus: - Mpa; tensile strength: 14 Mpa; elongation at rupture: 0.2 %; flexural modulus: 7.2 Mpa; bending strength: 31 Mpa; deformation under load temperature: 112°C. Advantages and disadvantages Pieces of color are obtained, with great aesthetic quality. No supports are needed. It is not easy to obtain functional pieces due to the fragility of the pieces obtained. The cost of the equipment is medium-high.

Table 7: Laminated manufacturing (LM).

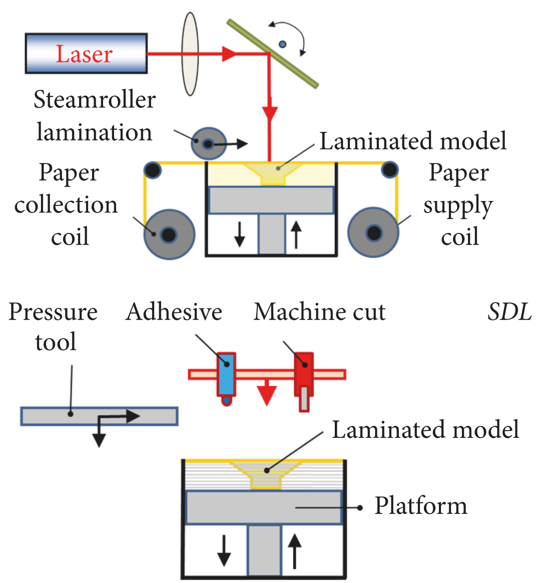
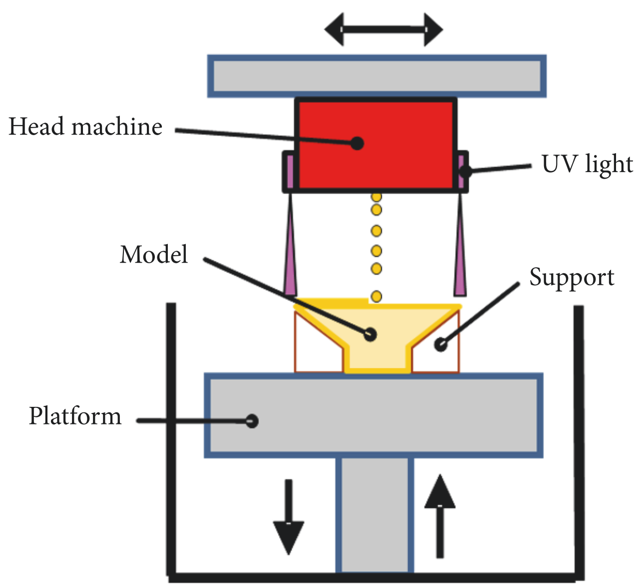
Selective Deposition Lamination	
	Invented in 2003 by MacCormack, SDL must not be confused with laminated object manufacturing (LOM) technology. LOM uses a laser, laminated paper and an adhesive that fixes the model and support material. The SDL technique works by depositing an adhesive in the area required, both of the model and the support, and a blade that cuts the outline of the layer [7]. LOM: The layer thickness is 0.165 mm. The maximum model size is 170x220x145 mm. SDL: Layer thickness corresponds to the thickness of the paper used plus that of the layer of adhesive. Sheets of PVC with the following properties are used: tensile strength: 40-50 Mpa; elongation at rupture: 30-100%; flexural modulus: 1200-200 Mpa; deformation under load temperature: 45-55°C. Advantages and disadvantages Pieces of high quality aesthetic objectives are obtained. The starting materials are low cost. The pieces obtained can be painted. The equipment is of average cost. No functional parts are obtained.

Table 8: Injection-polymerisation (JP-SL).

Resin Injection (Projection) and Ultraviolet Light Photopolymerisation	
	A head with thousands of injectors deposits drops of liquid resin that are hardened using two UV ray lights fitted on the sides of the selfsame head. Two materials can be used simultaneously (bi-material pieces) [18]. The minimum layer thickness is 0.017 mm. The range of materials is extremely extensive and includes translucent resins, polypropylene, ABS and elastic resins. Properties of the SCI White (PolyJet) material: tensile modulus: 2500 Mpa; tensile strength: 58 Mpa; elongation at rupture: 10-25 %; flexural modulus: 2700 Mpa; bending strength: 93 Mpa; deformation under load temperature: 48°C. Advantages and disadvantages The quality and surface finish are good or very good. Great precisions and transparent parts can be obtained. Equipment and materials are expensive. They have problems to obtain pieces with cantilevers or internal holes due to the difficulty of removing the supports.

as injection. A difference is made between directed energy deposition and material extrusion when both are, without a doubt, deposition processes.

Moreover, it is not justifiable to distinguish between injection processes when an "adhesive" or a "material" is injected, since, at the end of the day, both materials will end up forming part of the prototype or final part, as is the case of the ProMetal system.

It is also interesting to see that there are two types of injection: (a) when an adhesive is injected (which ends up forming a "material" part of the product) and (b) when a "material" is injected.

Lastly, there are different processes, some very important, that do not fall into any of the groups in this classification, such as in the case of mask sintering or digital light processing, for example.

ISO proposed, in its 2010 working draft, the following ten processes: stereolithography, laser sintering, laser melting, fused layer modeling/manufacturing, multijet modeling, polyjet modeling, 3D printing, layer laminated manufacturing, mask sintering, and digital light processing [32].

There is no doubt that for the simple fact of defining ten processes, other important processes are left out. In this classification, it can be seen that the manufacturers' considerations have more of an influence than logic. In 2015 ISO assumes the ASTM classification with its standard ISO/ASTM 52900:2015 (ASTM F2792).

An additive manufacturing system is in itself a production system and, therefore, for the purposes of classification, the systematics of manufacturing processes should be used. In every manufacturing system, there must be four elements present [4]:

(i) Material

(ii) Energy

(iii) Machine and tool

(iv) Technology (know-how)

From the point of view of the material, we could opt for the classic classification of solids, liquids, powder, etc. [14]; however, for both the engineer who wishes to manufacture the product and their customer, it is more important to expand upon the technical qualities of the material and, thus, we need to begin to classify the processes according to their ability to work with metal materials (with high melting points and which, therefore, require more energy in the process) or with other materials. And it is these technical qualities that we are going to focus on in this article.

From the point of view of energy, it is important to analyse what type of energy is required and how this energy is transmitted. With regards what type of energy is required, this may be as follows:

(i) Heat (electrical resistance, electron beam, etc.)

(ii) UV light (visible or laser)

(iii) Chemical energy (for adhesion processes, chemical reactions, etc.)

With regard to how this energy reaches the material for successful transformation, this may be via the following:

(i) Laser (valid to provide UV light and heat)

(ii) Electrical resistance

(iii) Electron beam

From the point of view of the machine, it is important to analyse the alternatives of smaller machines, suitable for offices, compared to industrial machines and as regards the tools, these shall include the following:

(i) Vats and containers for photosensitive liquids or powder

(ii) Deposition or extrusion nozzles

(iii) Injectors

With regard to technology, the most important variable, it is necessary to know if it is available commercially or if it is only an option available in research centres, as in this case there will likely be a wait involved, although fortunately not long if the technology is valid.

In conclusion to all of this, Table 9 shows the classification system that takes these variables into account: material, energy, machine and tool, and technology.

To specify this classification, which can cover all additive manufacturing processes with simple approaches and that can evolve as technology evolves, we present the classification chain of the five processes analyzed in the introduction, the basic pillars of additive manufacturing (Table 10).

For example, stereolithography (SL) is a process that uses resins as material (2); uses laser as energy (f); is a professional machine (3); uses vats and containers for photosensitive liquids as tools (a); and is available commercially (4). For this reason, stereolithography will have a classification: 2f3a4.

2.3. Analysis of the Environment. In order to carry out this study, we worked with leading additive manufacturing companies, both ones that are developing new processes and ones that are part of the market providing service. Contact was also established with researchers in technology centres and universities and their contribution has proved to be highly valuable.

Unsurprisingly, this study entails an exhaustive analysis of the most important literature in the field of additive manufacturing, a study that we cannot include in this paper in full due to the obvious space constraints. Nonetheless, a series of papers must be listed which, due to their special interest in the subject, provide information that has proved fundamental in producing this paper.

In the field of metal additive manufacturing, an analysis has been performed on processes using powder, whether powder injected, powder deposited in layers, or processes using wire [22, 33–35].

As has been discussed, this paper has been approached from both a professional perspective (expanding upon the most interesting innovations in this field) and a research perspective. Therefore, papers that take into account the social impact of additive manufacturing have been analysed

Table 9: Classification matrix of the processes in additive manufacturing.

Material	Materials with a low melting point (1)	Resins, transparent materials (2) Flexible materials (3)	Ceramics (4) Powder (5) Sheets (6)	Metals and difficult materials (7)
Energy	Heat Electrical resistance (a) Electron beam (b) High power laser (c)	Chemical energy Adhesives (d) Reagents (e)	UV light (visible or laser) Laser (f) or visible light (g)	Mechanical energy Cutting tool (h)
Machine and tools	Low cost (such as RepRap) (1) Vats and containers for photosensitive liquids or powder (a)	Office (2) Deposition or extrusion nozzles (b)	Professional (3) Injectors (c)	Industrial (4) Cutting tool (d)
Technology	In conceptual and development phase (1)	In experimental phase (2)	Available at research centre (3)	Available commercially (4)

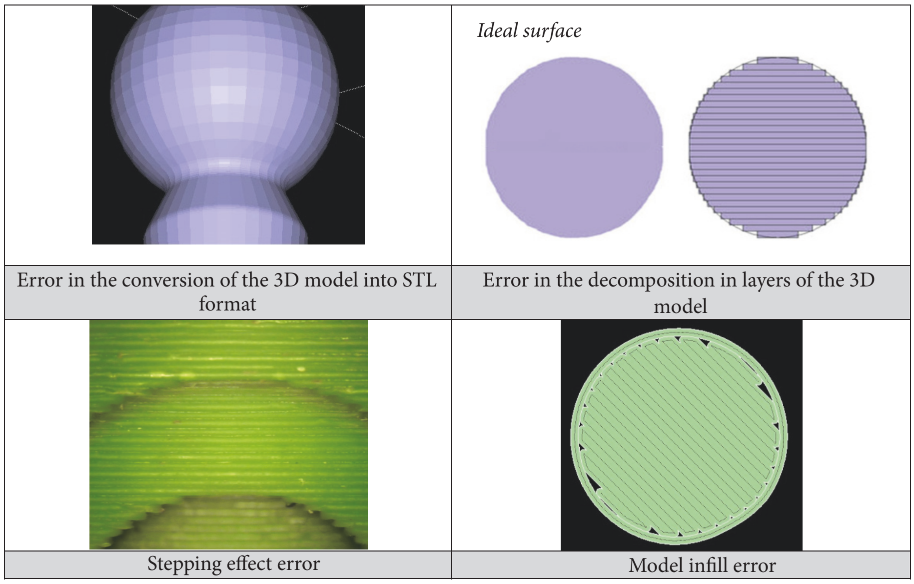


Figure 5: Technology limitations in the rapid prototyping process.

Table 10: Classification of the original processes in additive manufacturing.

Stereolithography (SL)	2 – f – 3 – a – 4
Selective Sintering (SS)	1 – c – 3 – a – 4
Material Deposition (MD)	1 – a – 3 – b – 4
Jet Prototyping (JP)	5 – d – 3 – c – 4
Laminated Manufacturing (LM)	6 – h – 3 – d – 4

[20, 35–37]. Papers focusing on medical issues have also been analysed [38–40] and papers have been located which expand upon design methodologies for additive manufacturing [6], the involvement of concurrent engineering [41], and the study of nonrigid materials [42]. The fields of architecture [23, 43–45] and the automotive industry have also been addressed [6].

References have also been found relating to functional prototypes [46], which show the use that additive manufacturing still has in this regard, along with papers on very contrasting environments, such as the food industry [47]. In the field of research, papers relating to studies of the processes [48] or medical studies with living cells [36, 38, 49–51] are worth mentioning.

Naturally, this study also considers the RepRap movement [5, 21, 52], as although technologically speaking it does not contribute much, it has undoubtedly played an essential role from both a social perspective and one of technology disseminations, and so it cannot be omitted in any serious study on additive manufacturing.

3. Analysis

3.1. Characteristics of the Models Manufactured Using the Addition of Material Technique. When the three-dimensional model is obtained using a reverse engineering process and the precision of the final model is determined by the scanning process, the virtual 3D modelling, and the additive manufacturing process. If an inverse engineering process has not been used, the models manufactured are determined by the virtual 3D modelling and the manufacturing process used [53].

We have already seen that during the manufacturing process the model is built by way of the depositing of layers on the x-y plane resulting in solid volume being acquired in the direction of the Z axis. This process is characterised by a volume error between the volume of the virtual 3D model and the volume of material obtained in the model and, therefore, the manufacturing precision is the result of superimposing different errors in the production of the model which affect the surface quality, the dimensional accuracy, and the final weight of the model.

The technology limitations that occur in this process are as follows: an error in the conversion of the 3D model into STL format (triangulation of the geometry), an error in the decomposition in layers of the 3D model (exact division of the thickness), stepping effect error (orthogonal deposition of the material by layers), and, finally, model infill error (Figure 5).

There are studies which show that the models obtained using rapid prototyping techniques have an average error in the majority of the 0.05 mm dimensions with respect to the original model or of modelling control in 3D [42].

The additive manufacturing of three-dimensional models with an aesthetic (visual) or assembly objective is achieved using techniques that involve the layer-upon-layer addition of plastic materials, while functional models or those capable of withstanding mechanical testing must be manufactured mainly in metal and, in some cases, in a polymeric material that is subjected to a postproduction hardening process.

Studies undertaken by different research institutes show that those products manufactured in metal using additive technologies provide the same or better mechanical performances than the same products manufactured using conventional processes [22]. The resistance to corrosion of

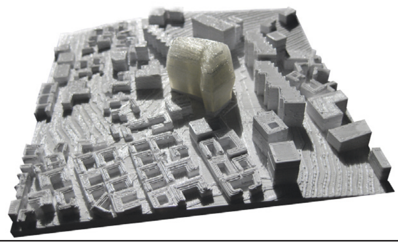
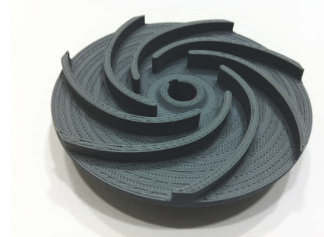
Model made for aesthetic (visual) purposes	Model made for hydraulic testing purposes
	

Figure 6: Function prototypes for testing.

products manufactured using additive technologies is similar where the same level of surface finish is involved.

One objective during research is that of obtaining functional prototypes using polymeric materials capable of withstanding mechanical testing using rapid prototyping technologies. The advances made in the field of deposition materials and the subsequent finishing of the model may lead to functional prototypes that do not require the use of techniques based on rapid manufacturing (RM), thereby avoiding tooling costs (see Figure 6) [23, 46].

3.2. Technologies and Decision Variables. Some of the technologies described above require the use of a material, known by the name of support material, the purpose of which is to hold any overhanging designed parts in place. Once the deposition process has been completed, the support material must be removed during an operation carried out subsequently to manufacture (postprocessing), and the technique used to remove it shall depend on the support material in question and, therefore, on the additive manufacturing technology employed. In some additive technologies there is no support material as the support function that is performed by the material that has not hardened [18].

With respect to the mechanical properties of the prototypes obtained via the addition of material, these are determined by the quality of the result of the fusion between layers and the properties of the material. The following parameters (DIN EN ISO 178/179/180/527/2039) must be established in order to analyse the mechanical properties of the materials used in the different additive manufacturing methods: elastic modulus, breaking stress, elongation, flexural modulus, impact strength, compressive strength, and melting point (Table 11) [11, 54–56].

The choice of the most suitable technique for each type of prototype is based on the definition of the objective behind the production of the prototype: aesthetic, functional, investigational, or visual if the purpose is only to check the external appearance of the item designed [19, 39, 42, 57–60]. When it comes to making this choice an analysis may be planned based on a study of the possible variables: technology, resolution and precision, materials, software, the mechanical properties of the material (traction, compression, impact, softening, and density), surface finish, production time, cost, maximum dimensions of the item or model, posthardening requirements, guarantee, noise, CE certification, operational temperature, electrical connections and consumption, interface (network, hardware, software and exchange formats), weight, and spares and consumables (Table 12) [23].

Of all the aforementioned study variables, those habitually taken into account when choosing the prototyping technology are *resolution-precision, the mechanical and thermal properties of the material, surface finish, production time, and the cost of the prototype.*

With respect to the evaluation of the different prototyping technologies in accordance with the cost of the prototype, the fact that the comparison of technologies is restricted by the type of machine used must be taken into account. It is commonly thought that those prototyping machines based on stereolithography (SL) and selective laser sintering (SS) can be applied to the industrial production of prototypes, while all the others are seen as being machines that can be used professionally, but not in situations where the main objective is production. The manufacturers are currently offering domestic or desktop, professional, and industrial rapid prototyping machines, and therefore the costs incurred by using these machines must be offset by the performance levels shown above and by the production levels that can be obtained [39].

However, to calculate the price of an element manufactured using additive technologies the following general model can be followed in which the final manufacturing cost of the prototype (C_p) of the 3D model has been calculated in accordance with the following equation [8]:

$$C_p = C_e + C_m + C_t + C_a \quad (1)$$

where

C_e is production cost (machine depreciation data)

C_m is cost of material

C_t is the processing cost of the 3D model and labour cost

C_a is finishing (post-processing) cost

If this calculation model is transferred to a specific case, observe the following example of the cost of a prototype generated using the MD technique in a professional grade machine that can be easily adapted to any additive technology. In this case, as can be seen, there is no finishing cost (Table 13).

Table 11: The principal mechanical and thermal properties of the functional materials used in AM.

PROPERTY	STANDARD	PROTOTYPING TECHNOLOGIES – HABITUAL MATERIALS							
		SL	SS	MD		JP		SL-JP	
		Next	PA 12	ABS	ABS+	VisiJet M3 X	zp150-Z-bond	Digital ABS	PolyJet White
Tensile modulus (MPa)	ASTM D638M2 DIN EN ISO 527	2370-2490	1650	1627	1915	2168	-	2600-3000	2500
Tensile strength (MPa)	ASTM D638M DIN EN ISO 527	31-35	48	22	37	49	14	55-60	58
Elongation at rupture (%)	ASTM D638M DIN EN ISO 527	8-10	20	6	4,4	8.3	0.2	25-40	10-25
Flexural modulus (MPa)	ASTM D790M DIN EN ISO 178	2415-2525	1500	1834	1917	-	7.2	1700-2200	2700
Bending strength (MPa)	ASTM D790M DIN EN ISO 178	68-71	-	41	62	65	31	65-75	93
Impact strength (J/m)	ASTM D256 DIN EN ISO 180	47-52	53	107	96.4	-	-	65-80	-
Deformation under load temperature (°C)	ASTM D648	48-57	86	76-90	73-86	88	112	58-90	48

Table 12: Decision variables when choosing a prototyping technology.

CHARACTERISTICS	SPECIFICATIONS TO BE CONSIDERED
COSTS	Price of the machine (including post-production and maintenance)
	Unitary model cost
	Cost of training qualified operators
	Control and modelling software
	Annual maintenance cost
DIMENSIONS	Workspace
	Dimensions of the machine
	Weight of the machine
	Noise level
	Mandatory accessories
WORK MATERIAL	Colour or number of colours, transparency
	Possibility of recycling material
	Technical characteristics of the material
	Working temperature
PRECISION	Precision
	Height/Thickness of layer
	Minimum detail size
	Resolution
	Minimum wall thickness
OTHERS	Vertical working speed
	Network/On-line connection
	Files supported, scope of the software associated with the machine
	Adaptability to accessories
	User friendliness (ease of handling and maintenance)

3.3. The Benefits and Disadvantages of Additive Manufacturing. The processes used to manufacture conventional parts and components are influenced by a series of limitations related to the obtaining of certain shapes, such as curved holes, mould release angles, or preventing tools from coming into contact with geometrically complex pieces. And then there is the fact that some manufacturing processes do not comply with a company's commitment to a sustainable production process by involving the residues related with the use of cooling liquids.

Two characteristics comprise the main difference between the additive manufacturing techniques and their conventional counterparts. These not only provide significant competitive advantages, but also do not make the manufacturing process more expensive:

(1) *The geometrical complexity of the part to be manufactured.* Elegant geometrical forms, hollow interiors, internal channels, variable thicknesses, irregular shapes, etc. can easily be reproduced based on the geometrical template obtained from a 3D CAD.

(2) *The customisation of the part to be manufactured.* Products that are exactly identical or completely different can be obtained without any notable influence on the process and without additional costs. This customisation represents one of the main current trends in the development of products with a high added value, and the mass application thereof is one of the paradigms pursued by the industrial sectors in developed countries, which see it as being the key to their sustainability.

These two characteristics can provide massive benefits in different industrial sectors:

(i) *Lightweight Products.* They enable the manufacture of products designed for a specific function and with made-to-measure features, e.g.: lighter for reasons of weight savings, strength or costs. Some of the additive manufacturing techniques are capable of filling a model with different degrees of porosity without a change of material.

(ii) *Multimaterial Products.* They make it possible to manufacture a product using several materials simultaneously in the same solid. This means that the technique overcomes one of the current limitations with respect to the weight/mechanical strength ratio by the introduction of new functionalities or the lowering of production costs [61, 62].

(iii) *Ergonomic Products.* The design of the components can achieve a greater degree of interaction with the

Table 13: Calculation of the prototyping cost using material deposition (MD) technique.

COSTS ANALYSIS FOR THE PROTOTYPING OF ITEMS IN A 3D PRINTER			
MACHINE DEPRECIATION DATA Ce			
Price of Machine (€)		25,000	
Yearly maintenance cost (€)		2,900	
Years of depreciation		4	
Depreciation (h/year) - 223 days-year / 8 hours-day		1,784	
Machine-depreciation price per hour (€/h)		**4.72**	
Retail sale price per hour (€/h)		**4.72**	
COST OF MATERIAL DATA Cm			
Cost of model material: ABS filament (€/cc) (€271-950 cc)		0.23	
Cost of support material: acrylic filament (€/cc) (€271-950 cc)		0.23	
Cost of tray material (€/unit): (€100-24 units.)		4.17	
COST OF TECHNICAL ANALYSIS DATA Ct			
Cost of technical model analysis – including release from mould (€/h)		20	
TECHNICAL DEPOSITION DATA			
Model type	***Mesh***		***Solid***
Deposition rate (cc/h)	11		16
Machine-deposition price per hour (€/h)			
ITEM TEST Model - Positioning: HORIZONTAL			
CONCEPTS BUDGETED	Solid Interior		Partial costs
Model material (cc)	17.32		€3.98 /unit
Model support (cc)	2.44		€0.56 /unit
Model time (h)	1.30		€6.14 /unit
Items per tray (unit)	1.00		€4.17/unit
Technical-analysis time (h)	0,30		€6.00
Number of items	1.00		
Unitary cost (€) + VAT	**€20.85 /unit**		
Total cost (€) + VAT	**€**		

user by adapting to the exact anthropometric characteristics of each individual (prostheses) without necessarily affecting the manufacturing costs.

(iv) *Integrated Mechanisms*. They make it possible to manufacture a mechanism that is totally embedded in the finished item without the need for subsequent assembly and adjustments, e.g., a journal bearing, a roller bearing, a spring and its support, and a screwed-on worm gear.

As far as the production of industrial components is concerned, the following must be highlighted as obvious benefits:

(i) *A reduction of the time it takes new designs to reach the market*: when additive manufacturing is used as a manufacturing technique of the end product and not only in the production of prototypes, many of the current launch and validation phases can be drastically shortened. Another advantage is that it provides great flexibility when it comes to responding to the continuous changes in market demand.

(ii) *Short production runs*: the size of the production run can be minimal to the extent of being on a per unit basis while hardly influencing manufacturing costs (if and when the depreciation of the equipment is not considered). One of the characteristics that make this possible is the lack of a need for tooling, which represents a considerable advantage with respect to the conventional manufacturing methods.

(iii) *A reduction of assembly errors and their associated costs:* ready assembled components can be obtained with the only subsequent operation being the quality control inspection.

(iv) *A reduction of tool investment costs*: tools do not form part of the additive manufacturing process. This represents a great deal of flexibility as regards adapting to the market and a reduction, or even elimination, of the associated costs (toolmaking, stoppages due to referred changes, maintenance, and inspection).

(v) *Hybrid processes:* it is always possible to combine different manufacturing processes. In this case combining additive manufacturing processes with conventional processes might be interesting to make the most of the advantages offered by both. For example, it might be extremely beneficial to combine additive manufacturing technology with mechanised material removal in order to improve surface quality via a reduction of the "stepping effect" produced by the additive manufacturing technologies. Hybridisation can also occur in the opposite direction, in other words manufacturing using subtractive methods starting with a block before adding, by way of additive manufacturing, those especially complicated characteristics which generate high value.

(vi) *Optimum usage of materials*: material wastage is reduced to a minimum. Any waste material can be easily recycled.

(vii) *A more sustainable manufacturing process*: toxic chemical products are not directly used in appreciable quantities.

However, additive manufacturing technologies do have a number of drawbacks which must be borne in mind when choosing the technology best adapted to the requirements of the product to be manufactured.

(i) Additive layer manufacturing produces what is known as the stepping effect. The disadvantages of this phenomenon include complicating the shaping of geometrical curves and an extremely rough surface finish. This effect means that shafts and holes must typically be manufactured with their circular cross-section in plan. If they are not, the roundness of the piece would not be acceptable. On the other hand, and putting roundness to one side, positioning the piece in another way might be useful depending on the application in question; it would be interesting to manufacture an overturned sliding axis in such a way that no 'interlocking' occurs.

(ii) With respect to some technologies, the manufacturing operation itself can be slow, thereby making it particularly suitable for small production runs. When the production run reaches a certain size it may well be appropriate to use a conventional technology despite the fact that, as has been seen above, these technologies have a number of limitations, especially geometrically speaking.

(iii) The materials used in some of the technologies might not be suitable for the product to be manufactured.

(iv) The depositing of layers produces anisotropic materials. Given the fact that many industrial components are subjected to forces that put the material under stress and that they are so sized as to use the minimum amount of material, it is possible that the performance of the components with respect to the forces they must withstand while in service results inadequate.

(v) The tolerances obtained using the majority of the additive manufacturing methods are still higher than those achieved using other manufacturing methods such as those based on the removal of material.

3.4. By Sector Innovation with Additive Manufacturing. Both in innovation and in research, advances are going to be defined by acquiring new materials, more precise, and less costly equipment and also by seeking out new sectors for 3D printing.

An interesting proposal in this field is that presented by Wong and his team in 2012 [6]. Six sectors are analysed: lightweight machines, architectural modelling, medical applications, improving the manufacturing of fuel cells, and additive manufacturing for hobbyist and additive manufacturing in art. We have no doubt that these were the sectors of innovation five years ago. However, our analyses show us that nowadays the additive manufacturing sectors where innovation can really be seen are as follows: consumer products,

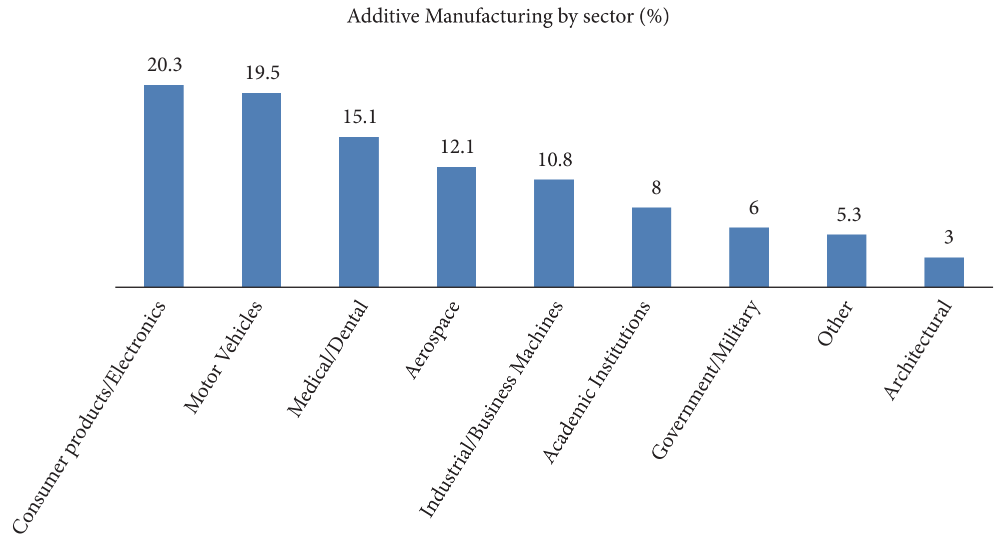


Figure 7: The use of additive manufacturing in the different sectors (Wohlers Report 2013).

automotive industry, medicine and medical engineering, aviation industry, architecture, construction, and food.

The degree to which additive manufacturing is used in different sectors is shown in Figure 7.

A review of the sectors in which additive manufacturing is currently used is presented as follows.

3.4.1. Consumer-Electronic Products. This sector uses additive manufacturing to obtain prototypes and models of a multitude of articles for the home, sports equipment, toys, etc. It is the number one customer of those additive manufacturing technologies that enable the direct digital manufacture of finished components of high geometrical complexity and that require customisation.

As soon as materials that are both flexible and strong even when thin become available, it shall be possible to manufacture consumer products such as clothes and footwear using additive techniques. The deposition of conductive materials via the printing of passive circuit components such as resisters, condensers and coils, diodes, organic light emitting diodes (OLEDs) and circuit interconnections can only benefit the production of electronic devices and components.

3.4.2. Motor Vehicles. In this sector additive manufacturing is being used to create prototypes that enable the validation of engineering processes and, above all, functional and aesthetic component design processes. The production of finished parts is not yet a reality, with the technique only being used in the customising of certain elements in one-off vehicles. The hope is that the development of new materials and their application of large, high-speed machines will favour the use of additive manufacturing in conjunction with the highly demanding production criteria inherent to this sector.

3.4.3. Medical/Dental. The application of additive manufacturing in the medical/dental sector enables physical 3D models to be obtained from processed medical images (3D scans, TAC) for application in different specialist areas.

The use of additive rapid prototyping technologies enables preoperative planning processes, the production of prostheses, and the preparation of surgical templates and guides to be carried out with a higher diagnostic quality and greater surgical safety in less time and more cheaply than is possible using conventional manufacturing techniques. In the case of specific and customised implants optimum planning of the surgical process and a reduction of operating times has already been achieved.

We must not omit today's 3D printing of living cells, bioprinting, in which a lot of resources are being invested and which we trust will soon present some very interesting results.

3.4.4. Aerospace. This market requires additive manufacturing to respond to high mechanical and thermal performance demands, weight reduction, and minimum losses of material as regards certain components with respect to both polymeric and metallic materials, primary titanium, and nickel alloys. The selective sintering of powdered metals has become a manufacturing, repair, and maintenance solution for certain components, e.g., turbine blades, as well as for the manufacture of high added value aeronautical tooling.

3.4.5. Architecture. The manufacture of mock-ups and prototypes within the architecture and construction sector was, and still is carried out on a significant handicraft basis. The development of assisted design systems, with its resulting progress towards solid modelling systems and the current BIM systems with respect to building, has enabled the production of highly attractive quality digital mock-ups, infographics, and virtual animation of plans and projects. However, the same cannot yet be said about the physical mock-ups obtained from that digital model of the plan using additive mock-up and prototype construction machines. 3D printing could well become an essential piece of equipment in the studios of architects and designers. In Figures 8 and 9, we can see a number of examples of how these techniques are

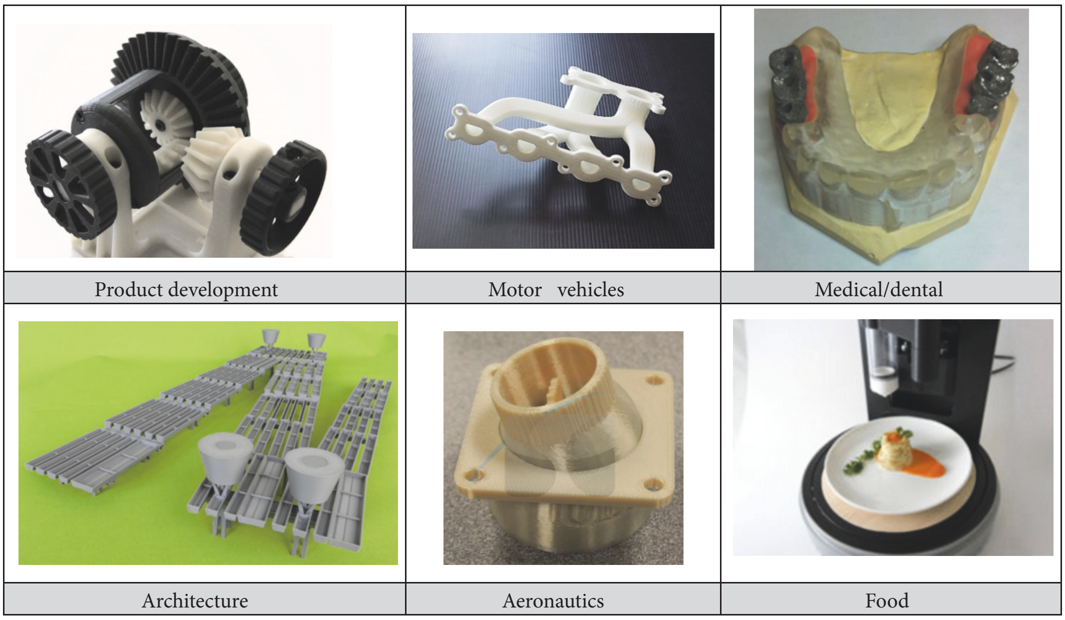


Figure 8: AM applications.

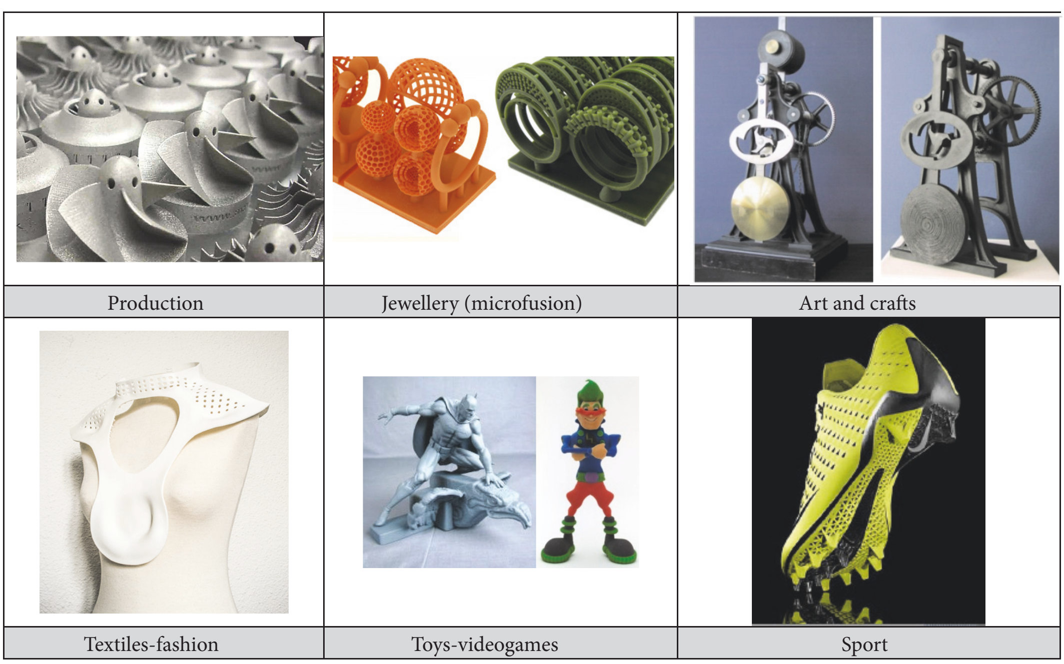


Figure 9: Another AM applications.

applied and they clearly show the great potential of additive manufacturing.

3.4.6. Food. Even when the catering industry is incorporating new 3D printing techniques for food, perhaps it is a good idea to discuss the advances being made in this field with regard to the food-health combination, that is, when 3D printing systems are used to measure out food and structure patients' diets.

However, naturally, in the field of catering and food in general, major advances are being achieved, which are already in operation in prestigious restaurants or in the production of desserts and sweets.

3.5. By Sector Investigation with Additive Manufacturing. In the field of research, that is, in the field of the work that is being carried out today in research centres and universities, both public and private, there are three approaches

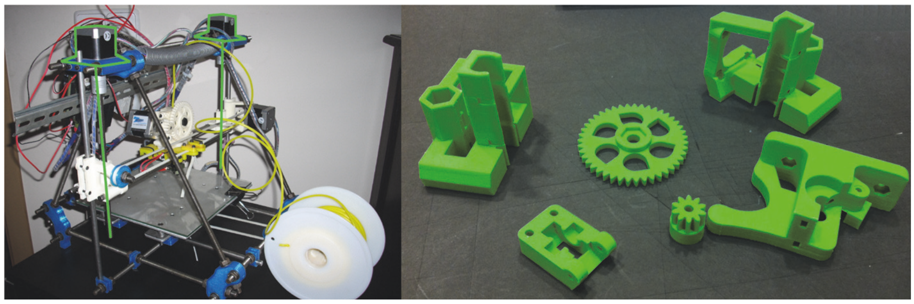


Figure 10: Example of RepRap machines and parts for replication.

that stand out: materials, equipment, and new fields of applicability.

In the field of new materials, a lot of progress is being made on biocompatible materials, compound materials, and metals, each one within a clearly identified field of development. In these fields, materials with good mechanical properties are also being sought; however, at the same time, progress is being made on the development of elastic materials, which open up a whole range of possibilities for 3D printing that is yet to be quantified.

In terms of new equipment, greater precision and lower cost are clearly what is being sought after, in order to make this technology competitive with regard to other conventional technologies.

With regard to the new fields of applicability in which, without a doubt, great progress will be made over the coming years in terms of printing metal materials, we resolve the problem of the dispersion of metallic liquid when it reaches molten state, and in terms of bioprinting, we develop new applications with regard to living tissues, not only in bones and cartilage, where advances have already been made, but also in other tissues of the human body, including the viscera and muscles.

3.6. The RepRap Community and Free Software. In 2004 Adrian Bowyer founded RepRap [5], an open-code initiative for building a 3D printer capable of printing out most of its own components, at Bath University. The vision of this project is to make the manufacture of low-cost distribution units available to people all over the world, thereby enabling them to create their own products on a daily basis (see www.RepRap.org).

As the term 'Fused Deposition Modelling' had already been registered by Stratasys, the RepRap Community has coined the term 'Fused Filament Fabrication (FFF)', which can be used by anybody without any restriction whatever (under a version 2 GPL licence). Under these terms and conditions anybody can distribute and modify the RepRap machine, but they must respect the modifications made under this licence [21]. In other words, all changes must remain in the public domain. As the machine is both free and open-code; anybody can, without having to pay any fees whatever, build an unlimited number of copies for themselves or for anyone else using the selfsame RepRap machines to manufacture the plastic parts of the copies (thereby making it self-replicating, Figure 10).

Although we know that the RepRap movement has played and continues to play a very important role in the development of additive manufacturing, it is interesting to discuss here that it was not initially accepted by the academic community, as it was considered a subject of minor importance. Only a few years later the subject was accepted, however not as a phenomenon in itself, rather under the consideration of a machine that could replicate itself, something that every manufacturing professional knows has been possible since the 19th century, with milling machines.

There is an increasing number of meetings of "experts" who analyse what the 'printing' of physical objects using 3D printers will represent, which is now being seen as one of the great industrial revolutions of the next few years, and there has even been talk of the Third Industrial Revolution. The #Redada sessions are a meeting that allows users and professionals to exchange ideas and analyse the possibilities open to them, as in the case of Video 34, "#Redada 18 Madrid: The Challenges of 3D Printing", which features a debate about the social trends and the aspects related to culture, civil rights, and technology.

3.7. User and Exchange Communities. The social importance of this technology has been enormous and, as has already been said, it is developing in leaps and bounds, thereby enabling engineering students and professionals who specialise in these particular techniques from all over the world to experiment with their creations and perfect them prior to the production of full scale versions.

Accessibility to the technology links a series of communities of users and developers who exchange their know-how and experiences in order to continue perfecting the printing system and open up new and previously unimaginable fields in the process.

Alongside this, these communities of users have developed a series of platforms for exchanging existing 3D models for downloading and printing, thus broaching a far from ludicrous idea that involves manufacturers making 3D models of ex-catalogue parts of their products available to users. To a certain extent Google Earth has already done this by allowing the community of Google Sketch Up users to upload models of buildings from all over the world in their exact location for everybody to enjoy. The fact that the future holds countless possibilities cannot be too highly stressed. There are model upload and download banks such as the English language platform Thingiverse and its Spanish counterpart Rascomras. Many more exist, and their number increases by the day, some more creative than others, such as The Pirate Bay (a community for the downloading of all types of audiovisual material which has incorporated a new section for 3D models).

The Clone Wars Projects seek to spread the word about RepRap technology while at the same time contributing new designs and innovative research channels, but not so much along self-replication lines.

A series of workshops have existed all over the world for a number of years now. Known as FabLabs (Fabrication Laboratories), they are being promoted by the Center of Bits and Atoms (CBA) of the Massachusetts Institute of Technology (MIT), at which a lot of hard work is being done on this technological revolution in light of the social changes it is bringing about. They are equipped with a series of computer-controlled machines "for building (almost) anything": 3D printers, laser cutters, CNC (computerized numerical control) routers and an electronics laboratory (among many others that vary from workshop to workshop). Worldwide, with respect to the number of Fablabs Spain ranks fourth with 7-8 behind the USA, with more than thirty, The Netherlands (9), France (8), and ahead of Germany (6).

4. Discussion

As has been discussed throughout this paper, additive manufacturing (AM) processes are considered in many applications as a new industrial revolution. This article conducts an exhaustive study of the current state of additive manufacturing. As is shown in Table 2, the technologies and processes that currently exist are very diverse and, therefore, producing a classification that unites and differentiates all of them being truly complex. Thus, this paper proposes several types of classifications.

Over recent years, many names have arisen to encompass these technologies, such as "rapid prototyping", "rapid tooling", "3D printing", and "freeform fabrication". All of these are commonly accepted; however, "additive manufacturing" is probably that which best brings them all together.

The main advantages associated with these technologies are the high precision, the possibility of using different materials, and the ability to obtain impossible prototypes using conventional means. The current limitations include the high cost of the processes, the time required to obtain the prototypes, and perhaps the lower resistance they have. Active work is underway to improve these limitations in order for additive manufacturing to be competitive with regard to other more conventional means.

It is important to note that within additive manufacturing there is no perfect technology for all purposes, rather what we need to do is to determine the most suitable technologies for a specific use.

For example, in the dental sector, as is discussed by Jiménez et al. (2015) [39], in order to manufacture the models used in the thermoforming of correction splints, technologies based on printing by injecting resin (IJP-UV), digital light processing (DLP), and fused deposition modeling (FDM) are the most suitable as they offer the best price-quality ratio of the model for thermoforming.

Among the agents in the aviation market, metal material additive manufacturing technologies, such as 'Electron Beam Melting' (EBM), 'Sintering Laser Melting' (SLM), or 'Laser Cladding' (LC), are those that attract most interest, in particular, for part manufacturing, case of the OEM or Tier1; or for part repair, case of the 'Maintenance and Repairing Overhaul' (MRO). These manufacturing technologies provide many advantages in comparison with other conventional metal transformation processes (http://www.ctsolutions.es).

Changing sector, 3D printing of architectural models will lead to a reduction in the number of steps, an improved design timeframe, and the preservation of the finer details of the final architectural design, and therefore its market niche is on the rise. As discussed by Domínguez et al. (2013) [23], fused deposition modeling machines appear among the most suitable for obtaining working models, given their low cost (especially in the case of the RepRap models), the speed of the process, and the possibility of recycling the material. Machines projecting binding agent would also be suitable for obtaining models for the client, thanks to their competitive prices, good surface finish, wide range of colours, and lack of support fixtures, among other qualities. Although, perhaps, the method most used for architecture is printing via the sintering of composite powder, this material requires a postprocess to harden it and give it the necessary consistency and finish for an optimum result (http://sicnova3d.com). In any case, it is certainly true that, right now, no technology fully meets all of the requirements of the work specifications in the field of architecture and construction. Thus, this sector still has quite a long way to go.

PolyJet technology produces ultradetailed prototypes, moulds, and even final parts that incorporate smooth rigid, transparent, and flexible materials, which is why it has been the technology most used in the jewellery sector in recent years. Multimaterial 3D printers produce lifelike models with a variety of properties on a single build tray (www.stratasys.com). Regarding jewellery, one of the advantages of using 3D printers is speed. The plastic parts take 7 to 10 days to be made, whereas metal parts take 10 to 15 days. Other positive points include the cost saving and the fact that it is possible to retouch the jewellery while it is being printed.

4.1. Immediate Future of Additive Manufacturing. In production lines, one of the main focal points for improvement in additive manufacturing consists of optimizing its features in order to be competitive with regard to conventional manufacturing processes in different production lines. In comparison with the traditional means, the use of additive manufacturing technologies continues to be too costly.

An important niche for saving in the industrial sector would be the so-called virtual libraries. There is a large number of fixed assets in all industrial platforms within what is known as physical replacement parts, spare parts, etc. Many of these items could be saved by means of a virtual parts library (https://www.thingiverse.com/, http://www.3dprintfilemarket.com/), which could print suitable parts or components as and when required.

Another important section is that of the study of new materials. Cellulose, the plant material we have used for centuries to make paper, has emerged as a new resource for better, faster, and cheaper three-dimensional printing, in addition to providing an alternative that is recyclable and biodegradable by nature, according to new research by the MIT, published in Advanced Materials Technologies. At present, the key raw material for 3D printing is polymers, compounds that are largely synthetic and which use inks to create three-dimensional objects in accordance with the models via a computer used to execute the three-dimensional printing (www.imprimalia3D.com).

A particularly interesting field and one for study is that of the space sector, where additive manufacturing should also play an important role. The National Aeronautics and Space Administration of the US (NASA) is seeking a habitat design built using a 3D printer that can be used as a base to build houses on the surface of Mars. The final objective is to achieve a space design that allows astronauts to stay on the red planet for long periods at a time. Different projects are being carried out to conduct research on materials and explore the possibilities of 3D technology, which would mean many of the necessary infrastructures could be directly built on the Moon using, moreover, resources that are already there. This would speed up this large undertaking, as it would notably reduce the amount of parts that would need to be taken to the Moon and then later to Mars. 3D technology and the use of resources may help reduce costs both in the long and in the short term.

4.2. Connected Industry: Future Prospects of Additive Manufacturing in the 4.0 Environment—A Study Is Conducted on the Possibility of Positioning Additive Manufacturing in a Service Environment. The term Industry 4.0 was coined to describe the smart factory, a vision of computer-aided manufacture with all of the processes interconnected through the Internet of things (IOT). It is what we know as the industrial Internet of things, I2OT.

It is hoped that the new concept of industry 4.0 will be able to drive forward fundamental changes on the same level as the steam-powered first industrial revolution, the mass production of the second, and the electronics and proliferation of information technology that characterised the third.

According to Mark Watson, associate director for the industrial automation of IHS, "The challenge for the fourth industrial revolution is the development of software and analytical systems that turn the deluge of data produced by intelligent factories into useful and valuable information."

Factories with fully computerized production processes are better prepared to respond faster to changes in the market, as they have integrated greater flexibility and individualization in their manufacturing processes.

However, in order to obtain real improvements in manufacturing efficiency and flexibility, manufacturers must be able to manage and analyse large amounts of data, the biggest challenge of which will be regarding software. Companies should implement Big Data systems capable of managing large amounts of data from the manufacturing environment and conducting an intelligent real-time analysis, providing valuable information for decision-making, thus optimizing the processes and increasing business intelligence.

Industrial companies have to take the technological leap to Industry 4.0, in the field of additive manufacturing. The concepts and experiences being accumulated in companies and research institutes need to be passed on to companies by means of guided visits to leading facilities, induction and practical training, guided training, diagnosis, specific advice, testing, and prototypes.

Why should additive manufacturing be introduced in companies in a connected industry setting? The answer is simple: because the following can be achieved:

(i) Creative product design
(ii) More customised products with high quality and performance
(iii) DDM (demand driven manufacturing) with less waste generated and efficient use of energy
(iv) Internet (EICTs in general) as a tool with a high potential to support new supply chain models
(v) The consumer as designer and "customiser"
(vi) Additive manufacturing as enabling technology

4.3. Additive Manufacturing and B2C/B2B. The majority of the work on systematizing and disseminating sales experience and on the techniques, methods, texts, and sales and marketing courses focuses on selling to the consumer, what we call B2C (Business-to-Consumer). However, the volume of business generated by sales to other companies, B2B (Business-to-Business), is much higher, not to mention complex and different.

Additive manufacturing can take the shape of a service activity and, therefore, it needs to adapt to ensure that the companies that are willing to provide this service obtain higher growth and profitability on sales to other companies and organizations and also on sales to the consumer, taking into account the final destination of the additive manufacturing service.

The current problem is that there is no vertical platform that organises the advanced manufacturing technologies and customised manufacturing based on additive manufacturing (3DP.)

Current service providers partially facilitate the transaction for 3DP solution companies. It must be ensured that additive manufacturing is on the cloud as a reliable service based on the fact that clients manage the details of their manufacturing project in real time: material, size, delivery time, quality, price, location, and catalogue payment (direct e-commerce selection), by means of a quotation or offer.

A global platform must be configured as a network of 3DP services: marketplace for B2B vertical offering (Figure 1). The service portfolio should be built around the following activities:

Business model: marketplace, all agents, all orders (large series focus), matrix selection, web location, and real-time all-agents capacity management.

(i) Market: B2B focus (could do B2C), KPI-customised orders.

(ii) Value Chain: global E2E services to B2B vertical clients.

(iii) Technology: E2E open API connecting in real-time clients and provider's ERP.

(iv) Product: Manufacturing and high quality / high definition.

(v) Expertise: Institute 3DP: industry, research centres, universities ecosystem.

However, the development of additive manufacturing does not stop there; the following step was what is now called "bioprinting", which is the printing of cells and living tissues [38, 50]. The interest in this is mainly due to the shortage of organs available for transplant and the possibility of avoiding rejection if the organ required can be successfully printed using the individual's own cells. Nevertheless, its use is very important in research on new drugs in order to reduce the use of laboratory animals.

3D printing of living cells usually requires the deposition of cells and also the deposit of the support element or matrix. This matrix, the place where the cells are going to grow, where nourishment will be found and on which the structure is to be formed, may be liquid, usually called bioink, paste-like, rigid solid, or elastic solid. Also, solid materials in particular may or may not be biodegradable [51].

The issue of biodegradation is an added factor in this technology, as if this biodegradation occurs too quickly; we will not obtain the desired results; however, if it occurs too slowly, there is a possibility that the structure will prevent the development of the cells and so, in the end, we will not obtain the desired results this way either. This is why bioprinting is currently the focal point of the majority of research projects: it is anticipated that bone regeneration, printing different vital organs, printing human skin, etc., will be functionally viable in the near future, as prostheses currently are.

5. Conclusions

(i) Conventional manufacturing is mainly limited by production run size and the geometrical complexity of the component, and we are occasionally forced to use processes and tools that raise the final cost of the element. What is more, some manufacturing processes do not comply with a commitment to sustainable manufacturing (contamination, recycling, etc.).

(ii) Additive manufacturing is one of the key tools for tackling the growth and the creation of added value and high quality employment.

(iii) Conceptually, the term 'additive manufacturing' describes the technology in general and it is used when referring to industrial component manufacturing applications and high-performance professional and industrial equipment. Other terms exist, with the best known being "*rapid prototyping and 3D printing*", in accordance with the scope of the model and the type of additive machine used.

(iv) Additive manufacturing techniques provide huge competitive advantages because they adapt so well to the *geometrical complexity and the customisation of the design of the part to be manufactured.* The following can also be achieved in accordance with the sectors of application: *lighter weight products, multi-material products, ergonomic products, short production runs, fewer assembly errors resulting in lower associated costs, lower tooling investment costs, a combination of different manufacturing processes, optimum use of material, more sustainable manufacture.*

(v) Even though this type of process began as a new independent technology, nowadays additive manufacturing is a manufacturing system more, comparable to others such as subtractive manufacturing or foundry. Therefore, the protocols for the classification of additive manufacturing processes do not have to be different from those applicable to other manufacturing systems.

(vi) The drawbacks are: *the finish of complex surfaces can be extremely rough, long production times, materials with limited mechanical and thermal properties which restrict performance under stress, higher tolerances than with other manufacturing methods such as those based on material removal.*

(vii) The study variables habitually taken into account when choosing the prototyping technology are: *resolution-precision, the mechanical and thermal properties of the material, surface finish, production time and the cost of the prototype.*

(viii) The manufacturing precision is the result of superimposing different errors in the production of the model which affect the surface quality, the dimensional accuracy and the final weight of the model. The errors that occur in this process are: an error in the conversion of the 3D model into STL format (triangulation of the geometry), an error in the decomposition in layers of the 3D model (exact division of the thickness), stepping effect error (orthogonal deposition of the material by layers) and, finally, model infill error.

(ix) Three-dimensional models with an aesthetic (visual) or assembly objective and functional models capable of withstanding mechanical testing can be achieved.

(x) Additive manufacturing can be applied across many sectors and it can be easily adapted to the demands of each of them.

(xi) Design and printing using 3D printers is seen as being one of the major industrial revolutions of the nest few years. Proposals exist for making the manufacture of low-cost RepRap distribution units available to people all over the world via communities of users and developers who exchange 3D models, know-how and experiences for optimising the manufacturing performance of a self-replicating 3D printer.

(xii) It still seems puzzling that the first scientific publications relating to the important movement that is additive manufacturing came to light several years after the development of the first inventions, the first patents and even the first commercial communications on the advance.

(xiii) It is also strange that the RepRap movement did not gain ground in academic environments at the beginning, and only found its niche when the movement was justified as "machines that can replicate themselves" when, as is known in technical environments, there were already milling machines available more than one hundred years earlier that were able to self-replicate.

(xiv) The choice of technology is directly dependent on the particular application being planned: first the application, then the technology. Laser systems are being increasingly used, especially in the field of finished part production. In the future, the use of print technology systems is going to increase by the day.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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