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UNIT 3

Additive manufacturing and 3D printing in Industry 4.0

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Contents

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Introduction

The newest industrial revolution, Industry 4.0, integrates intelligent production systems, such as additive manufacturing (AM) and 3D printing. This technology is considered to be an essential technology in this industrial movement. The rapid emergence of AM implies that new competences need to be acquired to adapt to the digital transformation.

In this unit, learners will be provided with an overview of additive manufacturing (AM) and 3D printing. They will be in touch with key concepts related to these areas, their applications and their implications in design and manufacturing in the industry 4.0 era. Thereby, learners are expected to acquire the knowledge and confidence they need to deliver these contents to their students/trainees and thus increase their awareness and preparation for career opportunities in the areas of AM and 3D printing.

Unit 3 — Additive manufacturing and 3D printing in Industry 4.0 — is divided in 4 subunits:

1. AM and 3D printing basic concepts;
2. AM: Processes, materials, and application areas;
3. 3D software for 3D printing;
4. Advantages and disadvantages of AM and 3D printing in Industry 4.0.

Learning Outcomes

	Upon completion of this unit the learner will be able to…	
Knowledge	Skills	Responsibility and Autonomy

Fundamental knowledge of AM and 3D printing in Industry 4.0: - basic concepts - materials - AM general process phases - deposition processes - benefits and limitations Basic knowledge of AM and 3D printing in Industry 4.0: - equipment - software - main application areas	Identify the concepts of AM and 3D printing in Industry 4.0 Recognise the main materials used in AM/3D printing considering their properties and applicability – metals, plastics, ceramics and composites, etc. Identify the main quality challenges related to the use of materials in AM/3D printing Summarise the steps of AM process phases: pre-processing, production and post-processing Describe the most used deposition/printing processes in AM/3D printing Explain the benefits and limitations of AM/3D printing in the Industry 4.0 era when compared to traditional manufacturing Distinguish the main equipment available in AM according to the deposition processes Classify AM/3D printing software in categories according to tasks: modelling, slicing, etc. Make use of Tinkercad software to design prototypes for 3D printers Recognise main application areas of AM in Industry 4.0: aerospace, automotive, healthcare, daily life objects, etc.	Raise awareness amongst trainees about the potential use of AM/3D printing in CC industries Propose 3D printing to produce unique daily life objects/parts Discuss the 3D design of an object/part considering the object/part application Use 3D printing technology when an advantage over conventional methods

EXTERNAL RESOURCES: computers, mouses, keyboards, TinkerCAD (3D CAD tool accessible through an online browser)

1.1 AM and 3D printing basic concepts

Advanced manufacturing is nowadays one of the key pillars of Industry 4.0. Among the available advanced production technologies is 3D printing, a technology that is revolutionizing the way objects are produced. The term 3D printing covers a host of processes and technologies that offer a full spectrum of capabilities for the production of parts and products in different materials.

3D printing, in many cases also called additive manufacturing (AM), uses computer-aided design (CAD) to build objects by adding layer by layer of materials. Thus, 3D printing refers to any manufacturing process which additively manufactures 3D parts in layers of materials from a CAD file (Image 1), which means that a digital model is turned into a physical three-dimensional object by adding material a layer at a time.

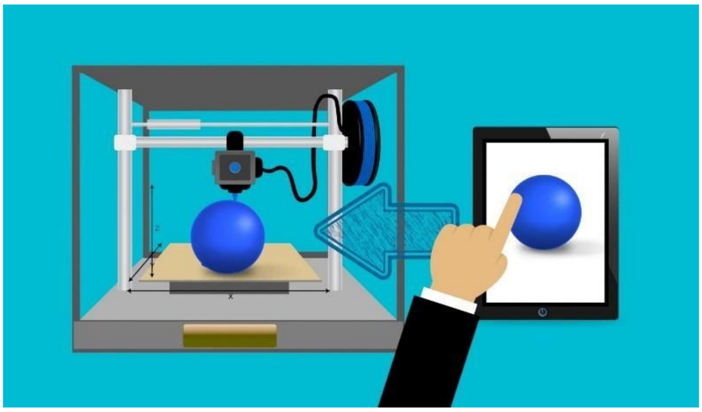

Image 1 – 3D printed object from a CAD file.

AM contrasts with traditional manufacturing, where material is removed (or subtracted) from a block of material until the final shape or part is achieved, something that is called subtractive manufacturing. Manufacturers see AM as a viable alternative in many cases where presently CNC machining or other technologies such as injection moulding or investment casting are being used.

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 some limitations).

Most AM processes follow these steps:

1. Take a 3D CAD model;
2. Slice model into layers and generate computer code;
3. Print first 2D slice and supports (if needed);
4. Increment height;

5. Print next layer;
6. Repeat steps 4 and 5 until finished;
7. Post process (if needed).

What is additive manufacturing?

The way a 3D printer works varies by process. For example, some melt plastic filaments and lay it down onto the print platform through a nozzle (Image 2), like a high-precision, computer-controlled glue gun). Others, like large industrial machines can use a laser to melt (or sinter) thin layers of material powders.

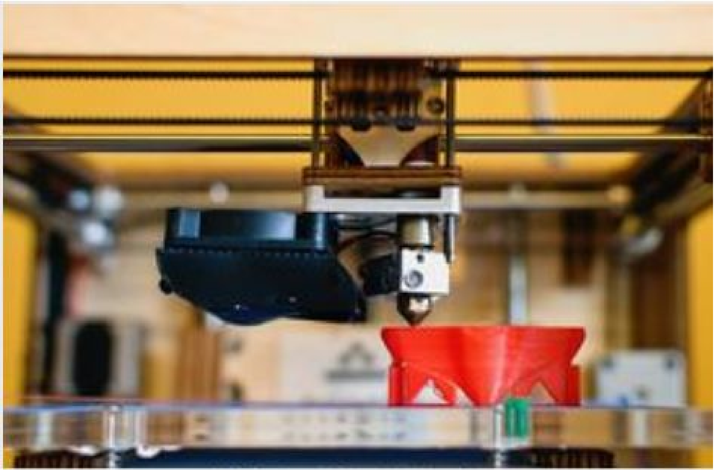

Image 2 – 3D printing of a polymeric part.

3D printed parts are rarely ready-to-use out of the machine though. They often require some post-processing to achieve the desired level of surface finish. For example, parts can be polished or smoothed by chemicals (Image 3), by blasting or tumbling to remove layer lines. These steps take additional time and usually manual effort.

Image 3 – 3D printed object before and after being post-processed.

The available materials also vary by process. Plastics are probably the most common (Image 4), but other materials, such as metals, have today an important presence in the 3D printing industry. The produced parts can also have a wide range of specific physical properties, ranging from optically clear to rubber-like objects.

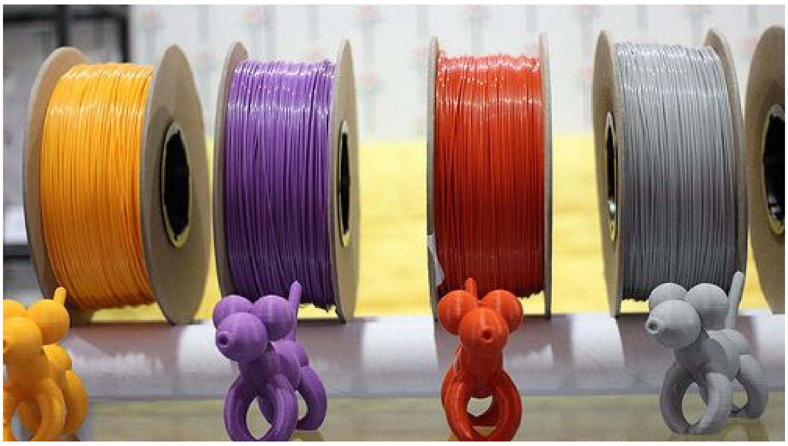

Image 4 – Many materials can be used for 3D printing.

Applications of 3D printing are emerging almost by the day, and this technology continues to penetrate more widely and deeply across industrial and consumer sectors: aerospace, automotive, energy, tooling, healthcare, education, etc. (Image 5).

Image 5 – Automotive components fabricated with AM technologies

3D printing today has found very specific roles in the world of manufacturing. The inflated expectations of the previous years have given their place to an increased productivity. Many aspects of the technology are now mainstream and adopted by both professional and hobbyists.

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3D printing would have the potential to create new industries and completely new professions, such as those related to the production of 3D printers and 3D parts. There is an opportunity for professional services around 3D printing, ranging from new forms of product designers, printer operators, material suppliers all the way to intellectual property legal disputes and settlements.

The use of 3D printing technology has potential effects on the global economy, if adopted worldwide. The shift of production and distribution from the current model to a localized production based on-demand, on site, customised production model could potentially reduce the imbalance between export and import countries.

1.2 AM: Processes, materials, and application areas

1.2.1 AM processes

There are many types of AM processes, each having strengths and capabilities, with specific areas of applications. ISO/ASTM 52900:2015 standard establishes and defines the terms used in AM, and categorizes this technology in seven individual processes. Despite having seven uniquely defined categories, there are many different methods within each category, but the overall technology and the underlying principle previously presented still apply (builds of physical 3D geometries by successive addition of material). The main differences exist within the materials, methods of deposition the layers, and type of adhesion between them. The seven AM processes are presented in Image 6.

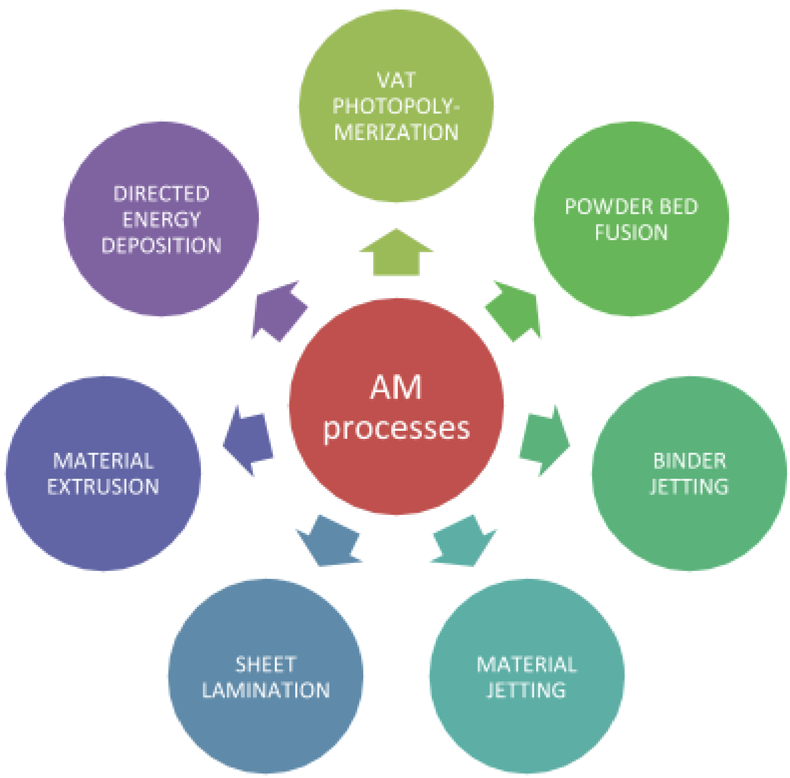


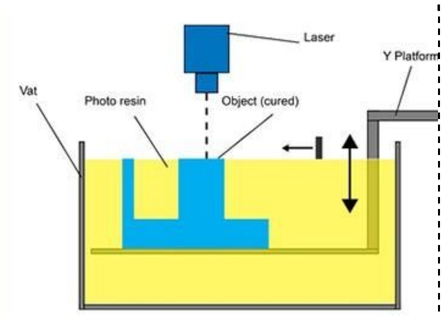
Image 6 – AM processes available in the industrial sector.

In the last decades, the focus of 3D printing has grown from making prototypes using vats of resin and beds of powder, to include the making of production parts with metal and ceramics. Table 1 shows an in-detail description of the main AM processes presented before. The same table also indicates alternative names for each process category (many of them trademarks).

[Vat polymerisation]

[Power bed fusion]

[Material extrusion]

Process	Description	Advantages	Disadvantages
VAT PHOTOPOLYMERIZATION SLA™- Stereolithography Apparatus DLP™- Digital Light Processing 3SP™- Scan, Spin, and Selectively Photocure CLIP™ - Continuous Liquid Interface Production  	Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.	• High level of accuracy and complexity • Smooth surface finish • Accommodates large build areas • Relatively quick process	• Relatively expensive • lengthy post processing time and removal from resin • Limited material use of photo-resins • Often requires support structures and post curing for parts to be strong enough
POWDER BED FUSION SLS™- Selective Laser Sintering DMLS™- Direct Metal Laser Sintering SLM™- Selective Laser Melting EBM™- Electron Beam Melting SHS™- Selective Heat Sintering MJF™- Multi-Jet Fusion	Powdered materials is selectively consolidated by melting it together using a heat source such as a laser or electron beam. All PBF processes involve the spreading of the powder material over previous layers. The process sinters/melts the powder, layer by layer. Layers are added with a roller in between fusion of layers. A platform lowers the model accordingly.	• High level of complexity • Powder acts as support material • Wide range of materials • Depending on material, structural parts can be produced	• Relatively slow speed • Size limitations • High power usage • Finish is dependent on powder grain size

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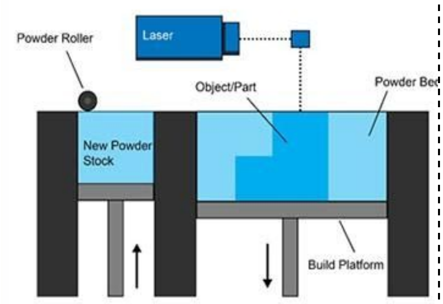
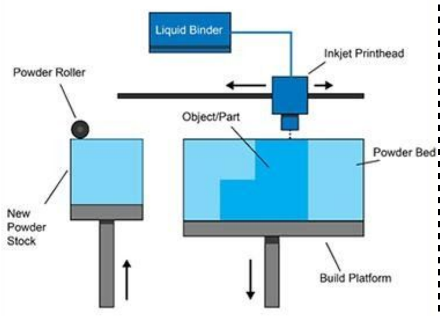
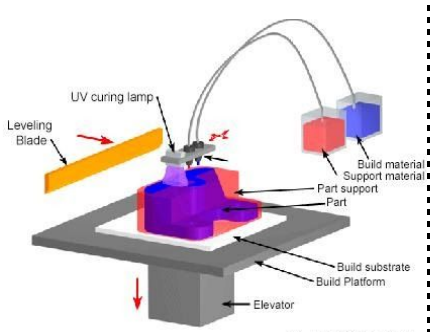
			
BINDER JETTING 3DP™- 3D Printing ExOne Voxeljet 	A powder based material and a binder are used. The binder acts as an adhesive between powder layers. A print head moves horizontally and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform. Parts are typically heated in a furnace after they are printed.	• Allows for full colour printing • Faster process • Uses a wide range of materials	• Not always suitable for structural parts, due to the use of binder material • Additional post processing can add significant time to the overall process
MATERIAL JETTING Polyjet™ SCP™- Smooth Curvatures Printing MJM - Multi-Jet Modeling Projet™ 	Material is jetted in droplets onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. The material layers are then cured or hardened using ultraviolet (UV) light.	• High level of accuracy • Allows for full colour parts • Enables multiple materials in a single part	• Support material is often required • A high accuracy can be achieved but useable materials are limited
SHEET LAMINATION LOM - Laminated Object Manufacture SDL - Selective Deposition Lamination UAM - Ultrasonic Additive Manufacturing	Sheets of material are stacked and laminated together to form an object. The lamination method can use adhesives or chemical bonding (paper/plastics), ultrasonic welding, or	• High volumetric build rates • Relatively low cost (non-metals) • Allows for combinations of metal foils,	• Finishes can vary depending on material but may require post processing to achieve desired effect

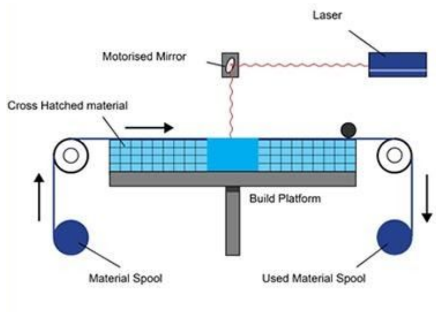
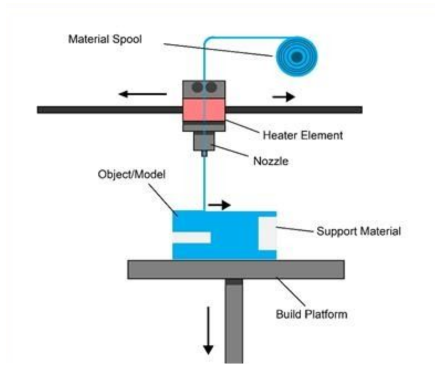
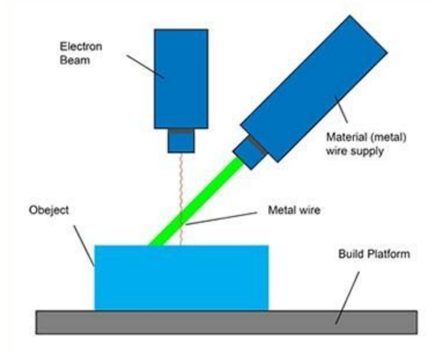
	brazing (metals). Unneeded regions are usually cut layer by layer and removed after the object is built.	including embedding components	• Limited material use
MATERIAL EXTRUSION FFF - Fused Filament Fabrication FDM™- Fused Deposition Modeling 	Material is extruded through a nozzle or orifice in tracks or beads, where it is heated, and then combined into multi-layer models. Common varieties include heated thermoplastic extrusion (similar to a hot glue gun) and syringe dispensing. It is a commonly used technique for domestic and hobby 3D printers.	• Inexpensive and economical • Allows for multiple colours • Can be used in an office environment • Parts have good structural properties	• The nozzle radius limits and reduces the final quality • Accuracy and speed are low when compared to other processes • Constant pressure of material is required in order to increase quality of finish
DIRECTED ENERGY DEPOSITION LMD - Laser Metal Deposition LENS™- Laser Engineered Net Shaping DMD™- Direct Metal Deposition WAAM™ - Wire-arc Additive Manufacturing 	Injected powder or wire is fed into a melt pool which has been generated on the surface of the part where it adheres to the underlying part or layers by using an energy source such as a laser, electric arc or electron beam. This is essentially a form of automated build-up welding.	• Not limited by direction or axis, being able to produce large parts • Effective for repairs and adding features, but also creating new parts • Multiple materials in a single part • Highest single-point deposition rates	• Finish quality can vary but usually requires machining and other post processing to achieve required features

Table 1 – Description of AM processes (images source: lboro.ac.uk).

1.2.2 AM materials

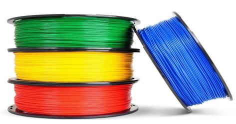
The materials available for AM and 3D printing have come a long way since the early days of the technology. There is today a wide variety of different material types that are supplied in different states (powder, filament, wire, pellets, granules, resin, etc.). Specific materials are now generally developed for specific platforms performing dedicated applications with material properties that more precisely suit the application. Each 3D printing process is compatible with different materials. Plastics (both thermoplastics and thermosets) and metals are by far the most common, followed by ceramics (Image 7).

VAT PHOTOPOLYMERIZATION	• UV-curable Photopolymer Resins (with various fillers)
POWDER BED FUSION	• Plastics, Metal and Ceramic Powders, and Sand
BINDER JETTING	• Powdered Plastic, Metal, Ceramics, Glass, and Sand.
MATERIAL JETTING	• Photopolymers, Polymers, Waxes
SHEET LAMINATION	• Paper, Plastic Sheets, and Metal Foils/Tapes
MATERIAL EXTRUSION	• Thermoplastic Filaments and Pellets (FFF), Liquids, and Slurries (Syringe Types)
DIRECTED ENERGY DEPOSITION	• Metal Wire and Powder, Ceramics

Image 7 – Typical 3D printing materials for the various AM processes.

Polymers and metals that are used today in 3D printing are detailed in Table 2.

AM Materials - 3D Printing's Greatest Challenge

Type of materials	Description
POLYMERS 	Common plastics can be used in 3D printing, including ABS and PC. The common structural polymers can also be used, as well as a number of waxes and epoxy based resins. Mixing different polymer powders can create a wide range of structural and aesthetic materials. The following polymers are usually used: ABS (Acrylonitrile butadiene styrene), PLA (Polylactide), including soft PLA, PC (Polycarbonate), Polyamide (Nylon), Nylon 12 (tensile strength 45 MPa), Glass filled nylon (tensile strength 12.48 MPa), Epoxy resin, Photopolymer resins.
METALS	A growing number of metals and metal composites are used for industrial grade 3D printing. A range of metals can be used, including a number of options suitable for structural and integral component parts. Common

	metals used are: Stainless steel (tensile strength: 1150 MPa), Maraging steel (tensile strength 1100 MPa), Titanium alloy Ti6Al4V (tensile strength 1150 MPa), Cobalt-chrome alloy Co28Cr6Mo (tensile strength 1300 MPa), Aluminium alloy AlSi10Mg (tensile strength 445 MPa), Gold and Silver.

Table 2 – Polymers and metals are the most popular 3D printing materials.

1.2.3 AM application areas

When the advances of additive manufacturing began, no one thought that this technology could revolutionize the industry to the extent that it has. While the main reason for its creation was to accelerate rapid prototyping, over the years, it has developed itself further than this, bringing great benefits, such as reduced material use, lowered costs, and production acceleration, to different sectors.

The evolution of 3D printing has seen a rapid growth in the number of companies adopting AM technology. 3D printing is efficient and highly customisable, and has potential applications
across a wide range of industries. The applications and use cases vary across those industries, and the potential sectors for 3D printing increase every day (Image 8).

Image 8 – Examples of application areas where AM is being used.

The following content highlights some examples of the most important areas that have been successfully adopting AM in the last years.

Aerospace & defence

Aerospace companies were some of the first to adopt additive manufacturing. Some of the toughest industry performance standards exist in this realm, requiring parts to hold up in harsh conditions. Engineers designing and manufacturing for commercial and military aerospace platforms need flight-worthy components made from high-performance materials. 3D printing delivers complex, consolidated parts with high strength. Less material and consolidated designs result in overall weight reduction – one of the most important factors in manufacturing for aerospace. The benefits of additive manufacturing for major companies and organizations continue to push forward the innovative designs and applications for the world of flight. 3D printing for aerospace isn't limited to prototypes. Real, functional parts are also being 3D printed and used in aircrafts. A few examples of parts that can be produced with 3D printing include air ducts (SLS), wall panels (FDM) and even structural metal components (LMD, DMD, WAAM), such as, turbine, engine, wings, fuselage, and spare parts.

AM for Aerospace & Defense: Innovating How Parts are Supplied

Automotive & transportation

Life in the fast lane means endurance to tough environments like extreme speeds and heat. The transportation industry needs parts that stand up to harsh testing and are lightweight enough to avoid unnecessary drag. With a wide array of rugged, high temperature materials and additive manufacturing technologies, and the ability to build very complex geometries, transportation companies are just scratching the surface of what can be made additively manufactured for their vehicles. Some of the applications that have transformed the industry include complex duct work that can't be fabricated with conventional manufacturing methods, resilient prototypes, elastomeric models, grilles, custom interior features and large panelling, engine and chassis components, moulding dies, jigs, fixtures and fittings. One of the most exciting applications realized today is the opportunity to reproduce aftermarket parts for restoring classic cars. While prototyping currently remains the main application of 3D printing in the automotive industry, companies are increasingly finding other use cases, such as tooling. Additionally, the several automotive companies are beginning to find innovate end-use applications for 3D printing, signalling an exciting development for the sector.

Healthcare (medical & dental)

The rapidly innovating medical industry is utilizing additive manufacturing solutions to deliver breakthroughs to doctors, patients and research institutions. Medical manufacturers are utilizing the wide range of high-strength and biocompatible 3D printing materials, from rigid to flexible and opaque to transparent, to customize designs like never before. From functional prototypes and true-to-life anatomical models to surgical grade components, additive manufacturing is opening the door to unforeseen advancements for life-saving devices, such as, orthopaedic implant devices, dental devices, pre-surgery models from CT scans, custom saw and drill guides, tools, enclosures and specialized surgical instrumentation. Currently, the medical and dental sector is estimated to represent 11% of the overall additive manufacturing market. The core strength of 3D printing for this sector is its ability to deliver on more personalised healthcare, in addition to opportunities to improve pre-surgical planning and drive device innovation.

Metal 3D printing for medical applications

Energy

Success in the energy sector hinges on the ability to quickly develop tailored, mission-critical components that can withstand extreme conditions. Additive manufacturing's advancements in producing efficient, on-demand, lightweight components and environmentally friendly materials provides answers for diverse requirements and field functions. Some key applications that have emerged from the gas, oil and energy industries include turbine parts, such as, rotors, stators, and nozzles, down-hole tool components and models, fluid/water flow analysis, flow meter parts, mud motor models, pressure gauge pieces, control-valve components, pump manifolds, and floating platforms components. With the development of corrosion resistant metal materials for customized parts that may need to experience under-water or other harsh environments, there's no telling what major energy companies may accomplish with additive manufacturing.

Industrial (machinery & tooling)

The industrial goods sector includes the production of machinery components, tooling and equipment used in the manufacture of other goods. With increasing production costs and the digitisation of manufacturing, industrial OEMs must constantly evolve to maintain operational agility and keep costs down. Manufacturers are therefore increasingly turning to 3D printing to stay agile, responsive, and innovative. The development of new 3D printing materials with high heat resistance and stiffness, combined with the ability to create custom parts quickly and at a low cost, pushed 3D printing to find multiple applications around industrial tooling. The ability to 3D print manufacturing aids, such as assembling jigs, gauges, guides, fixtures, and spare parts opens up a new range of possibilities for industrial goods manufacturers. In addition to jigs and fixtures, 3D printing is

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revolutionising the production of hard tooling like moulds, used in injection moulding and die casting. Now, metal 3D printing technologies like DMLS or SLM can be used instead, allowing tool-making companies not only to reduce material waste but improve the functionality of a mould. This can be achieved by integrating more complex-shaped cooling channels within the design, substantially improving the cooling characteristics of a mould.

3D Printing for machinery and production lines

Consumer products

For designers, graphic artists and marketing teams, the time it takes to form an idea and deliver it to the market is everything. Part of that time is simulating the look and feel of the final product during design reviews to prove ideas to key stakeholders. Consumer product manufacturers have embraced 3D printing to help develop iterations and quickly adjust design. 3D printing is great for producing detailed consumer electronics early in the product development life cycle with realistic aesthetics and functionality. Sporting goods have benefited from early iterations delivered quickly and with fine details. Other successful applications include entertainment props and costumes, lightweight models and sets, and finely detailed architectural models. As 3D printing technology advances in speed and build volume, more consumer products may turn to additive manufacturing for their large volume demands. When compared to pioneering industries like aerospace and medical, adoption of additive manufacturing within the consumer goods industry is still relatively young. However, the benefits of greater customisation, faster time-to-market and product development are increasingly recognised by the industry. A new freedom of design for creative industries including architecture, jewellery and entertainment where highly complex and bespoke items are required. Living hinges, interlocking parts, thin wall and hollow objects are possible for customised pieces. Metals can be finished using a number of processes for maximum visual effect.

Future applications of AM

1.3 3D software for 3D printing

For every stage of the 3D printing workflow, a specific software tool is necessary to go from the CAD file to the real printing object (Image 9).

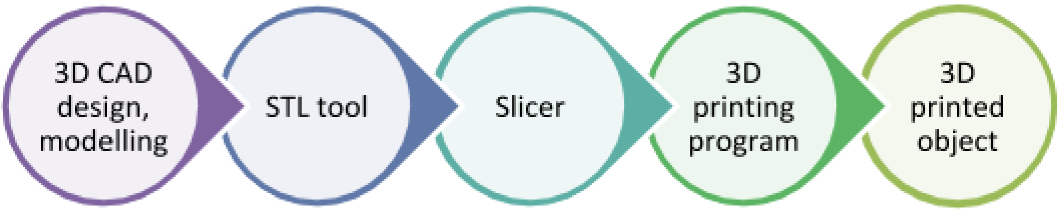

Image 9 – 3D printing workflow and respective software.

The 3D printing workflow consists usually of four major types of software, which do their work in series and make 3D printing possible:

- **3D design software** - design of 3D CAD models on the computer;

The CAD software is an important tool for professional architects, engineers, animators, and graphic designers. A CAD model will contain data like material properties, dimensions, tolerance and manufacturing process specific information. Furthermore, many CAD applications now offer advanced rendering and animation capabilities to better visualise product design. The most important is ease of interaction with and integration into the 3D printing process. Essentially this is the ability to generate 3D models that can be transformed into instructions for 3D printing. The most common way to accomplish this is to save the model in what's known as an STL file (an acronym for STereoLithography). For the most part, the modelling software must have an optimum balance between features, simplicity and price.

- **STL file software** - view, edit, and repair tool to fix problems on .stl files;

STL is the industry standard file format that all 3D printers understand. It uses triangles to represent the outer and inner surfaces of a solid 3D object. An STL file is not automatically 3D printable. Small mistakes in the design phase can make the 3D printing difficult with major flaws. The most common design mistakes, such as gaps in meshes, non-manifold geometry, floating surfaces, thin walls, and even big file sizes, can lead to misprints and failed prints. There are a range of STL repair tools that will help to identify the problems and even fix the models for successful printing.

- **Slicer software** - slice the 3D model into hundreds or thousands of flat 2D layers and provides instructions to the printer about how to print each layer;

Through the slicing process of the STL file, the 3D design is broken into two-dimensional flat layers that the printer will print in a stack. The number of slices generated depends both on the design and 3D printer. Also, the slicing process might add support material for the parts of the design that overhang lower printed layers. It is possible to allow the software to automatically add support material or the user can manually choose to add supports. In addition to slicing, the software can give the possibility to position the location of the print job relative to the print bed. Additional features allow for resize it, set the printing resolution and adjust the print head temperature and speed. After slicing, a print-ready file in G-code format will be obtained.

- **3D printer host software** - connects the computer to the 3D printer and handles all communication between the two devices. It also allows you to monitor the printing process and change settings in real time.

Table 3 lists most of the available free 3D printing software (free for students, educators, and open source projects).

Software	Function	Level	System	Website
3D Builder	Design	Beginner	Windows	3D Builder
3D Slash	Design	Beginner	Browser	3D Slash
Blender	Design	Professional	Windows, Mac, Linux	Blender
Figuro	Design	Intermediate	Browser	Figuro
FreeCAD	Design	Intermediate	Windows, Mac, Linux	FreeCAD
Fusion 360	Design	Intermediate	Windows, Mac	Fusion 360
OnShape	Design	Professional	Browser	OnShape
OpenSCAD	Design	Intermediate	Windows, Mac, Linux	OpenSCAD
Sculptris	Design	Beginner	Windows, Mac	Sculptris
SketchUp Free	Design	Intermediate	Browser	SketchUp
TinkerCAD	Design	Beginner	Browser	TinkerCAD

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Vectary	Design	Intermediate	Browser	Vectary
3D-Tool Free Viewer	STL Analysis	Intermediate	Windows	3d-Tool Viewer
MakePrintable	STL Editor, Repair	Intermediate	Browser	MakePrintable
MeshLab	STL Editor, Repair	Professional	Windows, Mac, Linux	MeshLab
Meshmixer	STL Editor, Repair	Intermediate	Windows, Mac	Meshmixer
3DPrinterOS	STL Editor, Repair, Slicer, 3D Printer Host	Beginner	Windows, Mac, Ubuntu, Raspberry Pi	3DPrinterOS
Netfabb	STL Repair, Slicer	Professional	Windows	Netfabb
KISSlicer	Slicer	Intermediate	Windows, Mac, Linux	KISSlicer
Slic3r	Slicer	Intermediate	Windows, Mac, Linux	Slic3r
SliceCrafter	Slicer	Intermediate	Browser	SliceCrafter
AstroPrint	Slicer, 3D Printer Host	Beginner	Browser	AstroPrint
Cura	Slicer, 3D Printer Host	Beginner	Windows, Mac, Linux	Cura
OctoPrint	Slicer, 3D Printer Host	Intermediate	Windows, Mac, Linux, Raspbian (as OctoPi image)	OctoPrint
Repetier-Host	Slicer, 3D Printer Host	Intermediate	Windows, Mac, Linux	Repetier
MatterControl 2.0	Slicer, 3D Printer Host, Design	Beginner	Windows, Mac, Linux	MatterControl
IceSL	Slicer, Design	Intermediate	Windows, Linux	IceSL

Table 3 – 3D printing software (source: all3dp.com).

3D printing and modelling workshop

1.4 Advantages and disadvantages of AM and 3D printing in Industry 4.0

The potential of AM and 3D printing as a new technology is incalculable. It's a technology that is changing the world as we know it. The number of applications based on AM is growing day by day and the full potential of the technology is still being explorer. Although AM and 3D printing have numerous benefits and advantages, as any other new or recent technology, AM is still being developed, and certain limitations or disadvantages are also present.

1.4.1 Advantages of AM and 3D printing

AM processes have received great attention in the past two decades, due to the advantages they can bring to the manufacturing businesses. Such advantages are broadly related to a positive impact on the life cycle of the product, whether in the manufacturing, use, or disposal phases. Thus, AM contrasts with traditional manufacturing where, for example, using different tools, material is removed (or subtracted) from a block of material until the final shape or part is achieved, something that is called subtractive manufacturing. Manufacturers see AM as a viable alternative in cases where presently CNC machining, injection moulding or investment casting are being used.

Image 10 – Main advantages of AM and 3D printing.

Some of the many advantages of AM includes (Image 10):

- **Design freedom** - greatly increased design freedom (ability to create previously unachievable complex shapes and geometries such as internal pathways, voids and structures), leading to increased functionality of parts or systems, as well as to weight savings, requiring less material due to high-efficiency designs;

- **Reduction in material usage** - improved sustainability of the overall part due to the reduction of material usage (minimal wasted material) and improves parts by making them lighter and stronger;
- **Less required tooling** - mass customisation due to a production based on negligible or less required tooling (dies, moulds, etc.);
- **Cost savings** - cost savings compared to conventional manufacturing methods and also through a reduction in non-recurring costs;
- **Reduction in lead times** - faster production and reduction in lead times (from CAD directly to production, without tooling);
- **Repair or remanufacturing** - reproduction of obsolete parts (otherwise unavailable as spare) allowing extended economic lifetime of production equipment.

[Benefits of Additive Manufacturing]

1.4.2 Disadvantages of AM and 3D printing

Whilst additive manufacturing has great potential it is still a relatively new technology and there are key areas for improvement and consideration when adopting the technology. AM is not always the right choice for product development. 3D machines have still potentially hazardous and wasteful. Moreover, their economic, political, societal, and environmental impacts have not been totally studied.

Image 11 – Limitations of AM and 3D printing.

Some limitations or disadvantages of AM are the following (Image 11):

- **High energy consumption** - according to some research studies, 3D printers consume much more energy than traditional manufacturing. From this point of view 3D printing is better suited for small batch production runs;
- **Expensive technology** - AM printing equipment and materials cost make the technology expensive, especially for metals. Nevertheless, with the expansion of the technology, prices are reducing every day;
- **Limited materials** - while 3D printing is a significant manufacturing breakthrough, material that can be used are still limited. However, many new materials are being developed every day for many industrial sectors;
- **Not for large scale production** - AM technology is more indicated for individual or small to medium batch productions. Still, industrial pilot lines are being tested to make AM adequate in certain cases for mass production;
- **Limited size of parts** - size of components that can be produced are usually limited to the machine chamber size. Exception goes to techniques where manipulators, such as robots, allow to fabricate very large parts;
- **Job losses** - with 3D printing technology is possible to make designs and prototypes in a matter of hours as it uses only one single step. It eliminates many stages that are used in traditional manufacturing and as a result, adopting 3D printing may decrease manufacturing jobs. Nevertheless, at the same time AM, as a new technology, needs trained people with new skills to be qualified for AM new jobs.

Other limitations are usually pointed out to AM such as the surface finish accuracy, the harmful emissions of processes and the lack of standardisation. As with any emerging technology, AM and 3D printing still have to be improved and explored to its full potential.

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