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Additive Manufacturing: from Rapid Prototyping to the Fourth Industrial Revolution

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Abstract. The paper analyzes the evolutionary path of additive manufacturing (AM), exploring its transition from a tool used exclusively for rapid prototyping to a mature production technology, a central pillar of the Industry 4.0 paradigm. The study emphasizes the shift in vision that additive manufacturing imposes on industrial design through the concept of Design for Additive Manufacturing (DfAM), which allows the creation of complex geometries that are impossible to achieve through traditional subtractive methods. In the context of the Fourth Industrial Revolution, the study highlights the integration of 3D printing with technologies such as Digital Twin, Artificial Intelligence, and Cloud Manufacturing, demonstrating how they converge to create smart and sustainable factories. Finally, current challenges related to standardization, material costs, and intellectual property are discussed, providing a perspective on the future in which additive manufacturing will redefine the circular economy and globalized production.

Keywords: Additive Manufacturing, 3D Printing, Industry 4.0, Rapid Prototyping, Production Digitalization, Technological Innovation.

1. Introduction: definition and evolution of AM Technologies

In recent decades, the global industrial landscape has undergone a profound metamorphosis, shifting from traditional subtractive manufacturing methods to advanced digital paradigms. At the center of this transformation is Additive Manufacturing (AM), popularly known as 3D printing, a technology that has long ceased to be merely a niche tool for designers.

Initially, additive manufacturing was adopted under the label of Rapid Prototyping. Its role was strictly limited: the rapid materialization of conceptual models to validate shape and fit, without making any claims to outstanding mechanical properties.

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Today, we are witnessing a paradigm shift. Thanks to advancements in materials science (high-performance polymers, metal alloys, composites) and equipment precision, the technology has migrated towards Direct Manufacturing, allowing the creation of final components used in broad fields: from industry to medicine. AM is considered the central pillar of Industry 4.0, enabling the transition from mass production to “mass customization” [1, 2].

The evolution of this new family of technologies is spectacular and can be divided into four distinct stages:

- **The Precursors Stage (1980-1987):** The first patents appear in Japan (Kodama) and France, but a lack of funding halts progress. In 1984, Chuck Hull patents Stereolithography (SLA), laying the foundations for the first commercial machine (SLA-1).
- **The Rapid Prototyping Stage (1988-1999):** Fundamental technologies emerge: FDM (Stratasys) and SLS (DTM Corp). In this phase, the technology is used only for visual models, with limited applicability, and the materials are generally non-metallic.
- **The Expansion Stage (2000-2010):** The expiration of early patents and the RepRap project (2005) transform AM into a global phenomenon. Equipment prices drop, and modeling software becomes accessible.
- **The Industrialization Stage (2011-Present):** The focus shifts to final parts, composite materials, metals, and bioprinting. AM becomes a viable production method for critical components in industry and medicine [3, 9].

2. Standardized classification (ISO/ASTM 52900)

According to international standards (ISO/ASTM 52900), AM processes are grouped into 7 categories [20, 21]:

- **Vat Photopolymerization (SLA, DLP):** Liquid resin cured by UV light.
- **Material Extrusion (FDM/FFF):** Thermoplastic filament melted through a nozzle.
- **Powder Bed Fusion (SLS, SLM, EBM):** Laser or electron beam melts layers of powder.
- **Material Jetting (PolyJet):** Photopolymer droplets are deposited and cured instantly.
- **Binder Jetting:** A liquid binding agent is deposited over a layer of powder.
- **Sheet Lamination (LOM):** Layers of material (paper, metal) are bonded and cut.
- **Directed Energy Deposition (DED):** Concentrated thermal energy (which can be a laser or electron beam – EBM) melts the material as it is deposited in successive layers of 0.03–0.05 mm.

Among all AM processes, the greatest impact has been and is currently made by Powder Bed Fusion (PBF), a process that exclusively uses metal powder of various qualities as raw material. The most well-known variants are SLM (Selective Laser Melting) and DMLS (Direct Metal Laser Sintering) [9].

PBF is the process with the highest impact because:

- Highly complex geometric structures can be manufactured (internal structures, cooling channels, or organic shapes impossible to achieve by milling or casting).
- The manufactured parts have a density of almost 100% and physical-mechanical properties similar to those of parts manufactured through classic technologies.
- It allows the simultaneous manufacturing of multiple identical or different parts, thus optimizing the workspace.

The applications of PBF processes are diverse across many fields, from industry to medicine:

- **Aerospace:** Fuel injectors or engine components lightened through generative design.
- **Medical:** Titanium hip implants, customized to the patient's anatomy, with porous structures that allow the bone to grow inside [7].
- **Dentistry:** Metallic dental crowns and bridges.

3. Design for Additive Manufacturing (DfAM)

The development and implementation of AM technologies, especially PBF, has had a major impact on design as well, bringing about a new design philosophy known as Design for Additive Manufacturing [3].

This means:

- **Topological Optimization:** Algorithms that eliminate material where there is no mechanical stress, resulting in parts with an “organic” appearance.
- **Lattice Structures:** The use of micro-geometric networks to reduce weight without sacrificing the structure's strength.
- **Part Consolidation:** The possibility of printing an assembly or subassembly of multiple parts as a single structure, eliminating assembly elements.

3.1 Topological Optimization (TO)

It is the “brain” behind modern design in additive manufacturing. It is the mathematical architect that decides where material should exist and where it should not.

TO is a mathematical method that optimizes material layout within a defined volume (design space), for a given set of loads (forces), boundary conditions, and constraints. Unlike traditional design, where the engineer draws a part and then checks if it holds up, in TO the engineer defines the forces, and the algorithm “draws” the part.

The most widely used algorithm in relevant software (such as Altair Inspire, Ansys, or Fusion 360) is Solid Isotropic Material with Penalization (SIMP). It works by dividing the design space into thousands of small elements called voxels (3D pixels). The algorithm assigns each voxel a density (ρ) between 0 and 1:

- $\rho=1$: Solid material (essential for the structure).
- $\rho=0$: Void (material can be eliminated).

The objective function is most often compliance minimization (maximizing stiffness). Mathematically, we seek to minimize the elastic strain energy:

$$\min c(x) = U^T K U \quad (1)$$

where U is the displacement vector, and K is the global stiffness matrix.

Topological optimization follows these steps:

- **Defining the Design Space:** The maximum volume the part can occupy in the assembly.
- **Defining “Keep Out” zones:** Areas that must not be modified (e.g., screw holes or contact surfaces).
- **Applying loads and constraints:** Where is the force applied? Where is the part fixed?
- **Running the simulation:** The computer successively removes material that does not bear tension.
- **Interpreting the result:** The result is often a “cloudy” or fragmented shape (STL mesh) that requires CAD finishing (re-surfacing) before printing.

In traditional manufacturing (CNC machining), shapes resulting from topological optimization are any mechanic’s nightmare. They have internal cavities, organic branching, and complex geometries that would require dozens of machine repositionings or would simply be impossible.

Additive manufacturing eliminates any difficulty in producing parts with complex geometric shapes because:

- **Complexity is free:** The 3D printer doesn’t care whether it prints a solid cube or an ultra-complex organic structure; processing time and cost are often lower for the complex part (because it uses less material).
- **Bio-mimicry:** TO results bear a striking resemblance to natural structures (bones, plant stems), because nature itself optimizes structures to consume the minimum amount of energy/material.

An example of topological optimization for Additive Manufacturing is a massive metal bracket that is analyzed by the Finite Element Method (FEA) and presented in Fig. 1 alongside optimization results compared to the existing variant manufactured by classic technologies.



Fig. 1 Aircraft Floor Bracket (<https://addupsolutions.com>).

Build Time on the FormUp 350 (at 50 μm): 11.50 hours; weight reduction from 3 kg down to 1.17 kg (a 61% reduction); time saved: 3+ hours.

A summary of TO benefits in Additive Manufacturing is presented in Table 1.

Table 1 Comparison between traditional design and topologically optimized design with AM

Criteria	Traditional Design	Optimized Design (TO + AM)	Effect
Shape	Geometric, simple (cubes, cylinders)	Organic, complex, biomimetic	Form follows function
Weight	High (redundant material)	Minimal (essential material only)	Lighter parts
Performance	Limited by manufacturing process	Maximized for function	Higher efficiency
Waste	High (by machining)	Minimal (additive)	Reduced raw material consumption

Although topological optimization seems like “the future”, it requires rigorous verification. Even if the software says the shape is perfect, we must ensure that the design also includes support structures necessary during 3D printing to avoid the part collapsing during manufacturing.

3.2 Lattice Structures

They are geometric configurations formed by repeating a unit cell in space. They have become fundamental in modern engineering, especially due to additive manufacturing (3D printing), and are geometric configurations formed from a network of interconnected micro-architectures, constituting a sort of highly ordered microscopic “scaffolding” that occupies a 3D volume.

They can be inspired by natural forms, such as the honeycomb structure found in beehives or the internal architecture of bones. These structures are characterized by their ability to reduce weight while maintaining high strength and stiffness, making them ideal for various engineering applications [3].

They have become stars in engineering with the rise of 3D printing (Additive Manufacturing), because they are nearly impossible to manufacture through traditional methods (milling or casting).

Their main characteristic is the efficiency of the strength-to-weight ratio. Practically, you can get a part that feels as light as air but withstands enormous pressure.

A lattice structure is formed by repeating a “unit cell”. Here is a synthesis of their classification and characteristics:

1. By unit cell topology

- **Strut-based Lattices:** Formed from segments connected at nodes (e.g., truss-like structures). Examples: Cubic, Octet, Kelvin.
 - **Triply Periodic Minimal Surfaces (TPMS):** Complex mathematical structures that do not have sharp nodes, but continuous curved surfaces. They are ideal for heat exchangers. Examples: Gyroid, Schwarz P, Diamond.
 - **Plate-based Lattices:** Formed from intersecting planes. They offer theoretical stiffness superior to strut-based ones.
2. By mechanical behavior
- **Stretch-dominated:** They are stiff and strong, but tend to yield suddenly. They are ideal for structural support applications.
 - **Bending-dominated:** They are more elastic and can absorb a lot of energy before breaking. They are used for impact protection or comfort (e.g., athletic shoe soles).

The use of lattice structures offers advantages that “solid” materials cannot match:

- **Exceptional Strength/Weight Ratio:** You can reduce a part’s mass by up to 70–90% while maintaining the necessary structural integrity.
- **Energy Management:** Due to porosity, they can absorb shocks and vibrations much more efficiently than dense materials.
- **Large specific surface area:** TPMS structures (Gyroid) offer a huge contact surface in a small volume, being recommended for cooling systems.
- **Thermal and acoustic properties:** They can be designed to soundproof or to direct heat flow in a controlled manner.
- **Heat Transfer:** Due to the large contact surface relative to volume, they are ideal for radiators or heat exchangers.
- **Osseointegration:** In medicine, implants with a lattice structure allow human bone to literally grow through them [7].

An example of a part redesigned with TO using Lattice structures, compared to the initial part, is shown in Fig. 2.

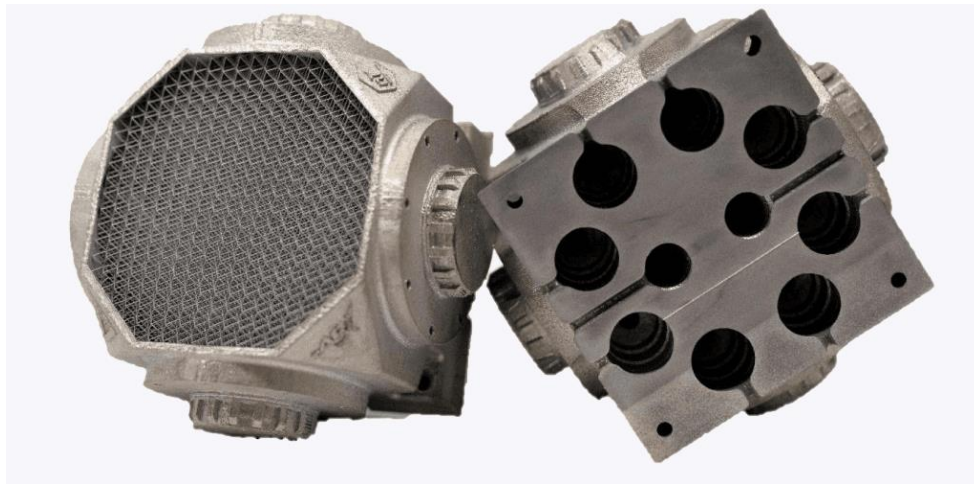


Fig. 2 Using the “shell & lattice” approach, Aerojet Rocketdyne reduced the weight of this spacecraft quad thruster block by 67% (<https://www.ntop.com/resources>)

In conclusion, Lattice structures represent a significant advancement in additive manufacturing, enabling the creation of complex geometries that were previously impossible with traditional manufacturing methods. Their ability to combine lightweight design with high performance makes them a valuable tool in modern engineering and product development. As additive manufacturing technology continues to evolve, the use of lattice structures is expected to expand across various industries, driving innovation and efficiency.

3.3 Part Consolidation

In additive manufacturing (AM), part consolidation is one of the most powerful design strategies. It consists of redesigning an assembly made of multiple individual components into a single unitary, complex part.

This approach is possible only due to the geometric freedom offered by 3D printing, which eliminates the restrictions imposed by traditional mechanical machining (milling, turning) or casting.

Consolidation doesn't just mean "gluing" parts together, but a functional optimization that brings benefits throughout the entire production chain.

These are:

- **Mass reduction:** Eliminating fasteners (screws, nuts, rivets) and joining flanges significantly reduces the total weight.
- **Increased reliability:** Every joint is a potential point of failure (leaks, galvanic corrosion, loosening via vibrations). A monolithic part eliminates these risks.
- **Simplified logistics:** Instead of managing inventory for 20 different items, you manage a single product code (SKU).
- **Reduced assembly time:** The labor hours required for assembly and checking assembly dimensions are eliminated.
- **Fluid performance:** In the case of internal channels (e.g., fuel injectors), consolidation allows smooth curved paths, impossible to obtain through drilling, reducing pressure losses.

A representative case is the GE Aviation fuel injector for the LEAP engine, illustrated in Fig. 3:

- **Before:** The injector was composed of 20 individual parts assembled with great difficulty into a subassembly.
- **After:** Topological optimization allowed the creation of a single 3D-printed part.
- **Result:** The part is 5 times more durable and 25% lighter, featuring internal cooling channels impossible to achieve through conventional methods.

A representative study for topological optimization and additive manufacturing is a rocket body part (Fig. 4), manufactured via SLM from superalloys (IN718) with the following advantages:

Innovation: Regenerative cooling channels are integrated directly into the chamber walls. In traditional manufacturing, these channels would have required hundreds of welding points, each being a potential point of failure. **Result:** Reduction in manufacturing time from months to 69 hours, a massive increase in reliability, and weight reduction.



Fig. 3. GE Aviation fuel injector for the LEAP engine, consolidated from 20 parts into a single 3D-printed component (GE Additive_Path to Production_White paper_Final.pdf)



Fig. 4 Rocket body manufactured via SLM.

4. Impact on Sustainability and the Circular Economy

The impact of AM technologies on sustainability is not just an incremental improvement, but a paradigm shift in how we design, produce, and consume goods. Here is how AM transforms the linear economic model (take-make-throw) into a circular and sustainable one [10, 11, 15]:

4.1 Resource Efficiency and Waste Reduction

Unlike traditional “subtractive” methods (milling, turning), where up to 90% of the raw material can end up as swarf, AM builds objects layer by layer.

- **Material usage:** Only the strictly necessary amount is used to create the part.
- **Closed-loop recycling:** Many leftover metal powders or plastic filaments can be reprocessed and reused in subsequent printing cycles.
- **Topological optimization:** AM allows the creation of structures that use less material while maintaining the exact same mechanical strength, reducing raw material consumption dramatically.

4.2 Local Production (“Digital Warehouses”)

By transitioning to digital manufacturing, physical inventories can be replaced with digital ones. Instead of producing thousands of spare parts and shipping them globally, companies can send CAD files to be printed locally, close to the end user. This significantly cuts down on global shipping emissions and logistics footprint [11].

4.3 Extending Product Lifespan

- **Advanced repairs:** Expensive industrial components (e.g., turbine blades) can be repaired by adding material exactly in the worn areas using processes like Directed Energy Deposition (DED), instead of being completely replaced.
- **Spare parts for discontinued products:** AM allows manufacturing parts for old appliances whose production lines no longer exist, thus preventing the entire appliance from becoming electronic waste.

4.4 Sustainability Challenges

Although the benefits are major, we must be realistic regarding the critical aspects:

- **Energy Consumption:** 3D printers can sometimes consume more energy per produced unit than high-volume injection molding.
- **Emissions and Health:** Melting processes can release volatile organic compounds (VOCs) or fine particles if not managed correctly.
- **Recyclability of complex materials:** New blends of materials (composites) can be harder to separate at the end of the life cycle.

The conclusion is that AM is a catalyst for sustainability by design. Moving from mass production to mass customization and distributed manufacturing represents the main technological solution to decouple economic growth from the intensive use of natural resources.

5. Critical Analysis: Myths vs. Reality in the AM Industry

The Additive Manufacturing (AM) industry has long suffered from excessive “hype”, being presented as a magic solution to any production problem. To understand the true maturity of the technology, we must separate marketing enthusiasm from the technical and economic reality in factories. Here is a critical analysis of the most common myths relative to current reality [8, 11]:

5.1 The Myth “Complexity is free”

Myth: AM allows the creation of any shape without additional cost.

Reality: While complex geometries do not require expensive tooling, they often necessitate extensive design time, complex support structures during printing, and meticulous post-processing.

Analysis: Complexity is not entirely free; the cost is simply shifted from the manufacturing tool to the design and post-processing phases.

5.2 The Myth “AM replaces traditional manufacturing”

Myth: 3D printing will completely replace CNC machining and injection molding.

Reality: AM is fast for prototyping, but extremely slow for mass production. While an injection molding machine produces a part in seconds, an industrial printer might need tens of hours for the same object.

Analysis: AM is economically efficient only for low volumes (high-mix, low-volume) or for parts with huge added value (e.g., medical implants, aerospace components). It will complement, not replace, traditional methods.

5.3 The Myth “Zero waste reduction”

Myth: Because it is an additive process, there is no material loss.

Reality: In powder bed fusion (PBF) processes, not all unused powder can be recycled infinitely. Thermal degradation limits the number of reuse cycles. In addition, the support structures mentioned earlier become waste immediately after production.

Analysis: Although much more efficient than milling, AM still generates technological waste and consumes a significant amount of energy to maintain printing chambers at high temperatures.

5.4 The Myth “Anyone can manufacture anything, anywhere”

Myth: We will all have printers at home and print spare parts, eliminating factories.

Reality: Printing critical parts requires rigorous quality control, certifications, and controlled environments. A printed metal part is not ready for immediate use: it needs heat treatment to eliminate internal stresses and precision finishing.

Analysis: Intellectual property (IP) and legal liability in case of failure remain major barriers to distributed production at the consumer level.

In conclusion, AM technology is not a replacement for traditional production, but a strategic complement. Its real value does not lie in the mass production of trivial objects, but in the capacity to create products with superior performance (lighter, more thermally efficient) that would be impossible to achieve otherwise.

6. The Future of Additive Manufacturing

The Future of Additive Manufacturing (AM) is no longer about “printing objects”, but about intelligent integration into a digitalized industrial ecosystem. If the last decade was about validating the technology, the coming years will be about scalability, smart materials, and autonomy [5, 13, 14].

Here are the main directions that will define the evolution of AM:

6.1 New Dimensions: 4D Printing and Multi-material

We are moving from simple polymers and standard alloys to materials that interact with the environment.

- **4D Printing:** Objects that change their shape or properties over time under the influence of external stimuli (temperature, humidity, light). Imagine a medical stent that expands exactly when it reaches body temperature.
- **True Multi-material:** The ability to simultaneously print metal, plastic, and electronic circuits in a single process, completely eliminating assembly stages.
- **Bio-printing:** The evolution from simple support structures to the printing of living tissues and, eventually, functional organs for transplant.

6.2 “End-to-End” Automation and Robotics

The biggest current barrier, manual post-processing, will be eliminated by autonomous production cells.

- **Hybrid production lines:** Robots that move the part from the printer directly to the heat treatment station, CNC finishing, and laser inspection, without human intervention.
- **Swarm Manufacturing:** Swarms of mobile robots equipped with printing heads working together to build large-scale structures (buildings, aircraft fuselages) directly on-site [10].

6.3 Artificial Intelligence and “Digital Twins”

AI will become the brain of the manufacturing process, reducing the failure rate (which is still significant today in industrial AM) [5, 14].

- **Real-time correction:** Machine learning algorithms that monitor each layer via video cameras and adjust laser parameters “on the fly” if they detect an anomaly.
- **Generative Design:** Engineers will no longer draw parts; instead, they will input the constraints (weight, forces, budget), and the AI will generate hundreds of optimized variants that only AM can produce.

6.4 Impact on the Business Model: “Product-as-a-Service”

The future of AM will force companies to shift from selling physical products to selling access or performance. By leveraging digital inventories and on-demand local printing, businesses can optimize supply chains and offer highly customized services, deeply transforming traditional manufacturing paradigms [12].

6.5 Sustainability as a Standard, not an Option

In the future, AM will be the engine of the circular economy through:

- **“Cradle-to-Cradle” Materials:** Exclusive use of recycled metal powders and biopolymers.
- **Energy Efficiency:** Use of renewable energy to power local micro-factories, reducing transport emissions by up to 90%.

6.6 The Future of Medicine through the Lens of Additive Technologies (AM)

This is no longer a subject of science-fiction, but a clinical reality in full expansion in 2026. We are moving from the universal “gold standard” to precision medicine, where treatment is shaped according to the unique biology of each patient [7]. Here are the main directions that will transform the medical system in the coming years:

- **Bioprinting: From Tissues to Organs**

The most spectacular frontier is 3D bioprinting, which uses “bio-ink” (stem cells and hydrogels) to create living biological structures.

- **Mini-organs for testing (Organ-on-a-Chip):** In 2026, laboratories are already using printed “mini-livers” or “mini-kidneys” to test new drugs, reducing the need for animal testing and accelerating treatment approval.
- **Skin and cartilage grafting:** Direct printing of skin onto wounds (for burn victims) or cartilage for knees is becoming an increasingly common procedure, eliminating the risk of rejection since the patient’s own cells are used.
- **Organ transplantation (Horizon 2030+):** Although printing a completely functional heart is still a major technological challenge, research in 2026 has

made huge strides in vascularization (creating the blood vessel network), which is essential for the viability of large organs.

- **Personalized Pharmacy: “Polypill”**

3D printing of medicines transforms the way we take pills.

- **Exact doses:** Instead of cutting a pill in half, the printer in the pharmacy can produce a tablet with exactly 12.5 mg of active substance, adapted to your weight and metabolism.
- **Polypill:** A single 3D-printed capsule that contains multiple different active ingredients, formulated to release at different times throughout the day, drastically simplifying the daily regimen for chronic patients.
- **Surgery and “Perfect Fit” Implants**

AM has already become the standard for orthopedics and neurosurgery [7].

- **Patient-specific surgical guides:** Before a complex operation, surgeons print an exact 3D model of the patient’s skull or spine to simulate the intervention, reducing time in the operating room by up to 30%.
- **Biomimetic bone implants:** 3D-printed titanium has a porous structure that allows natural bone to grow *through* the implant, making it much more stable in the long term than classic prostheses.
- **Bioresorbable stents:** Personalized cardiovascular devices that support the artery and then dissolve naturally in the body after fulfilling their role.
- **Democratization of Medical Devices**
- **Accessible prosthetics:** Organizations like e-NABLE have already demonstrated that hand prosthetics can cost tens of dollars instead of thousands, becoming accessible in developing countries or for children who need new prosthetics rapidly as they grow.
- **Point-of-Care:** Modern hospitals in 2026 are beginning to have their own AM units, printing sterilized surgical instruments or customized orthoses right at the patient’s bedside.

7. Conclusions: A Future Manufactured, Not Just Designed

The present paper aimed to demonstrate that Additive Manufacturing (AM) has moved past the stage of technological curiosity, becoming an essential catalyst for Industry 4.0.

Analyzing its evolution allows the formulation of the following fundamental conclusions:

7.1 The Paradigm Shift: From Form to Function

If in its early stages AM was used exclusively for rapid prototyping (form visualization), today the focus has shifted to functional performance. The ability to produce parts with complex geometries, impossible to achieve via traditional methods, enables topological optimization and weight reduction in critical sectors such as aerospace and medicine.

7.2 Integration into the Circular Economy and Sustainability

AM is not just a production method, but a sustainability tool. By drastically reducing material waste and enabling on-demand spare part manufacturing (“digital warehouses”), the technology directly contributes to the circular economy model, lowering the carbon footprint of global logistics.

7.3 Remaining Challenges

Despite rapid advancements, widespread adoption still faces hurdles, primarily:

- Processing speed and the high cost of special materials.
- The need for rigorous standardization and certification, especially in medicine and aviation.
- **The skills gap:** the need for a new generation of engineers trained in “Design for Additive Manufacturing” (DfAM).

In conclusion, Additive Manufacturing does not replace traditional methods but complements them, opening the doors to an era of smart production. If the 20th century was defined by standardization and mass production, the 21st century, under the aegis of AM, will be defined by agility, customization, and radical resource efficiency. The Fourth Industrial Revolution is no longer about what we can manufacture, but about how intelligently we can grow the products of the future.

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Notations

AM – Additive Manufacturing
DfAM – Design for Additive Manufacturing
PBF – Powder Bed Fusion
SLM – Selective Laser Melting
DMLS – Direct Metal Laser Sintering
SLA – Stereolithography
FDM/FFF – Fused Deposition Modeling / Fused Filament Fabrication
SLS – Selective Laser Sintering
EBM – Electron Beam Melting
DED – Directed Energy Deposition
LOM – Laminated Object Manufacturing
TO – Topological Optimization
FEA – Finite Element Analysis
SIMP – Solid Isotropic Material with Penalization
TPMS – Triply Periodic Minimal Surfaces
VOC – Volatile Organic Compounds

$c(x)$ – compliance (objective function in topological optimization)

U – displacement vector

K – global stiffness matrix

ρ – voxel material density ($0 \leq \rho \leq 1$)

References

- [1] Gibson I., Rosen D.W., Stucker B., *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, Springer Nature, 2021.
- [2] Gebhardt A., *Understanding Additive Manufacturing: Rapid Prototyping, Rapid Tooling, Rapid Manufacturing*, Hanser, ISBN 978-3-446-42552-1.
- [3] Diegel O., Nordin A., Motte D., *A Practical Guide to Design for Additive Manufacturing*, Springer, ISBN 978-981-13-8281-9.
- [4] Anderson C., *Makers: The New Industrial Revolution*, Crown Business, ISBN 978-0-307-72097-2.
- [5] Tsai F.M., Kurrahman T., Lim M.K., Sethanan K., Tseng M.L., *Artificial intelligence in green production and industrial engineering: challenges and future perspectives*, Journal of Industrial and Production Engineering, 2025, p. 1–22.
- [6] Alhawari O., Geng Z., *Advanced Manufacturing Systems: Bibliometric Leading Aspects and Conceptual Analysis*, Proceedings of the 12th International Conference on Production Research – ICPR Americas 2024, Springer Nature, 2025, p. 61.
- [7] Haberla M., *Development of the 3D printing market and its application in medicine*, Ekonomia – Wroclaw Economic Review, **29**, 2, 2023, p. 107–119.
- [8] Berman B., *3-D printing: The new industrial revolution*, Business Horizons, **55**, 2, 2012, p. 155–162.
- [9] Frazier W.E., *Metal additive manufacturing: a review*, Journal of Materials Engineering and Performance, **23**, 6, 2014, p. 1917–1928.
- [10] Hager I., Golonka A., Putanowicz R., *3D printing of buildings and building components as the future of sustainable construction?*, Procedia Engineering, **151**, 2016, p. 292–299.
- [11] Weller C., Kleer R., Piller F.T., *Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited*, International Journal of Production Economics, **164**, 2015, p. 43–56.
- [12] Aung P., Juha S., Jaakko H., Jaro V., Matti G., Mika L., *Usability and User Experience in an Industrial Metaverse: A Mixed-Methods Study of the Necoverse Point Cloud Inspection System for Shipbuilding*, Future Internet, **18**, 3, 2026, p. 160.
- [13] Singh S., Vasa L., *Global Artificial Intelligence Development Across Innovation Computation Industrial Power and Societal Impact*, 2026.
- [14] Gunakala K.K., *AI-driven automation for aerospace manufacturing: enhancing quality control through integrated systems*, Journal of Computer Science and Technology Studies, **7**, 3, 2025, p. 644–650.
- [15] Wolfgruber K., Koch V., Zunk B.M., *Analysis of the Transformation of the Manufacturing Industry and Engineering Education due to Sustainability Agreements*, Procedia Computer Science, **277**, 2026, p. 1171–1180.
- [16] Wohlers Associates, *Wohlers Report 2024/2025/2026 – Additive Manufacturing and 3D Printing State of the Industry*, <https://wohlersassociates.com> (last accessed: April 2026).
- [17] Deloitte University Press, *The 3D printing pay-off: Mind over matter*, <https://www.deloitte.com> (last accessed: April 2026).
- [18] European Commission, *Additive Manufacturing: The Next Step in the Digitisation of Manufacturing*, <https://research-and-innovation.ec.europa.eu> (last accessed: April 2026).
- [19] McKinsey & Company, *The additive manufacturing strategy: From prototypes to production*, <https://www.mckinsey.com> (last accessed: April 2026).
- [20] ASTM International, *Standard Terminology for Additive Manufacturing Technologies*, ASTM F2792.
- [21] ISO/ASTM 52900, *Additive manufacturing – General principles – Terminology*.

- [22] 3D Hubs / Protolabs, *Trend Reports on 3D Printing*, <https://www.protolabs.com> (last accessed: April 2026).