TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue 1, Month, 2026

CUSTOMIZATION AND SUSTAINABILITY THROUGH 3D PRINTING: APPLICATIONS FROM AUTOMOTIVE TO CONSUMER PRODUCTS

Marinela COSMA, Horațiu VERMEȘAN

Abstract: *This paper provides an overview of Fused Deposition Modeling (FDM), from its first patent to widespread adoption as a core additive manufacturing technology. The working principle, advantages, and limitations are discussed, with emphasis on cost efficiency and design freedom. Common filaments and reinforced materials are reviewed in terms of physical–mechanical properties and applications. Several world-premiere 3D-printed applications are presented, such as the first car, an electric motorbike, and a jet-powered drone. From a sustainability perspective, FDM enables material reuse and waste reduction, achieving savings of up to 70%. Industrial case studies, including automotive (Volkswagen, BMW), military drones (British Navy), medical orthoses (BioNeek), and footwear (MIT–Adidas, Zellerfeld), demonstrate FDM's expanding role in mass customization across multiple sectors.*

Key words: *3D printing, filament, mechanical properties, custom products.*

1. INTRODUCTION

Additive Manufacturing (AM) has become an adopted technology across various sectors such as medical, aerospace, and automotive, due to its ability to directly fabricate functional prototypes and components with complex geometries. This technology was first introduced in the late 1980s as a rapid prototyping solution, offering the possibility to quickly manufacture a virtually designed part and obtain a physical model through the successive building and solidification of material layers. The world's first 3D-printed model was created in 1983 by Chuck Hull (Figure 1), the inventor of stereolithography (SLA) technology. The SLA process was the first patented 3D technology and laid the foundation for the rapid prototyping revolution (US Patent US4575330A, issued in 1984; see reference [1] for details).

3D Printing or AM, refers to a set of processes capable of producing a wide range of structures and complex geometries directly from digital models [2]. Post-processing operations for 3D-printed parts may include support removal, surface polishing, sintering, infiltration, and heat treatments aimed at relieving internal stress and improving mechanical properties. Moreover, AM enables the fabrication of components that are difficult or nearly impossible to manufacture using traditional subtractive or formative techniques such as multi-material parts or biomedical implants, including artificially modeled organs [3-5]. In addition, AM technologies can significantly reduce production time and manufacturing costs, offering a high degree of flexibility and customization.

However, it should be noted that AM parts often exhibit anisotropic properties, due to the layer-by-layer fabrication method. Depending on the material used, AM domain encompasses various technologies [6-10].

Fig. 1. World's first 3D-printed part by Chuck Hull (1983). Source: www.3dsystems.com.

Received: 17.01.26; **Similarities**: 16.02.26: **Reviewed**: 19.02. /28.02.26: **Accepted** 24.03.26.

2. FDM PROCESS

Fused deposition modeling (FDM) also known as fused filament fabrication is one of the most widely adopted and accessible AM technologies. This method involves the controlled extrusion of a thermoplastic filament, layer by layer, to build a solid three-dimensional object. The FDM process was patented in 1989 by Scott Crump, co-founder of Stratasys, under U.S. Patent No. US5121329A: Apparatus and Method for Creating Three-Dimensional Objects [11]. A summary of this patent is presented in Figure 2.

The patent US5121329A expired in 2009, which led to the emergence of various manufacturers on the market. Currently, there is significant competition among FDM equipment producers, and the prices of these machines have decreased considerably. Hobby-grade machines start at approximately €300-€1,000. Professional-grade machines start from €5,000 and can reach up to €100,000. Some examples of hobby-level FDM printers tested by the authors, which produce good quality parts, include: Anycubic Kobra 2 Max, Bambu Lab Lab X1E Combo, Creality K2 Plus Combo, and Prusa i3 MK3S. On the other hand, examples of professional equipment include: Stratasys F370, Markforged Onyx Pro (Gen 2), Ultimaker S7, innovatiQ TiQ 5, and Omni3D Omni500 LITE. Due to its low cost, material versatility, and user-friendly operation, FDM technology is extensively used in industry, education, and by hobbyists.

Over time, industrial activities have severely affected water, air, and soil quality by releasing pollutants such as plastics, sulphur and nitrogen oxides, organic compounds, heavy metals and their derivatives, which pose serious risks to both ecosystem integrity and human health [12]. There is a compelling global demand to develop environmentally sustainable products, highlighting the importance of continued research aimed at discovering innovative solutions to enhance the performance of materials [13]. From sustainability perspective, FDM process offers significant opportunities for material reuse and waste reduction. For example, BMW recycles waste used parts into new filaments for printing tools and components across its global plants. Since 2018, the BMW program has expanded to process over 12 tonnes annually, enabling sustainable production using FDM fabrication [14]. The new components printed are ergonomic solutions for workers, scratch protection, fitting aids, manufacturing equipment, gauges, templates, and specialized tools. Zellerfeld, a footwear manufacturer, implements a closed-loop recycling process. Once customers return their worn shoes, printed entirely from TPU filament, the shoes are shredded, and new filament is generated for reprinting, reinforcing the company's commitment to a circular lifecycle with minimal waste [15]. These cases illustrate how FDM contributes to global efforts toward eco efficient production while reducing environmental impact.

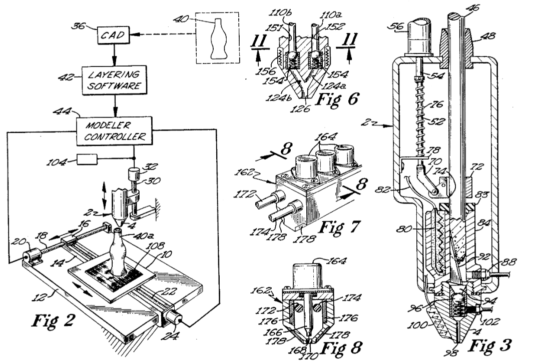

Fig 2. First patent of the FDM process 1989 (U.S. Patent No. US5121329A), titled "Apparatus and Method for Creating Three Dimensional Objects" [11].

The advantages of FDM technology include:

- Low cost of both equipment and filament materials, making it accessible for hobbyists, educational, and industrial users.
- Ease of use, with a user-friendly setup and minimal calibration required for most desktop systems.
- Material versatility, offering compatibility with a wide range of thermoplastics, such as PLA, ABS, PETG, and TPU.
- Efficient prototyping, enabling rapid part fabrication with minimal material waste.

However, FDM also presents several limitations:

- Weak interlayer adhesion, particularly when printing parameters (e.g., temperature, speed, layer height) are not optimized, which can compromise mechanical strength.

- Rough surface finish, inferior to that produced by subtractive methods (e.g., CNC machining) or resin-based methods (e.g., SLA or PolyJet).
- Dimensional inaccuracy, especially on larger parts, with typical tolerances around ±0.20 mm and ±0.4% above 100 mm.
- Support requirements, as overhangs and complex geometries often necessitate the use of support structures, which add time and post-processing effort.

2.1 Available filaments

The study examines widely used filaments such as PLA, ABS, PETG, TPU, and Nylon. The standard filament diameter is 1.75 mm, as it offers precise extrusion control and compatibility with the majority of FDM printers on the market. However, a 2.85 mm filament is available, and it can be advantageous in high-volume or large-format printing, as it allows higher material flow rates. The choice between 1.75 mm and 2.85 mm typically depends on the printer design, the intended application, and the desired balance between speed, precision, and reliability.

Table 1 presents a concise comparison of the advantages and disadvantages of 1.75 mm and 2.85 mm filaments for quick reference.

2.1.1 PLA

Polylactic acid (PLA) is a commonly adopted material in FDM manufacturing, favored for its printability, visual appeal, and environmental friendliness. PLA is a biodegradable polyester derived from renewable resources such as corn starch or sugarcane. Its processing characteristics make it highly accessible: PLA softens at relatively low temperatures and exhibits negligible thermal distortion during fabrication. These properties simplify calibration and reduce the likelihood of print failure, especially for basic desktop printers.

This material is offered in a broad palette of colors and textures, making it ideal for decorative objects or early-stage product prototypes. Compared to ABS, however, PLA is more brittle and less flexible, which can be a limiting factor in mechanical applications. Despite these trade-offs, reliability, visual quality, and ease of use associated with PLA continue to make it a primary material of choice in desktop 3D printing environments. The performance characteristics of PLA-printed parts are outlined in Table 2, and an example component is shown in Figure 3.

Fig 3. PLA filaments produced by UltiMaker and topology-optimized bracket fabricated.

While PLA is classified as biodegradable, its degradation occurs only under specific industrial composting conditions, which maintain elevated humidity and temperatures above 40–60 °C [16]. After 90 days, studies have shown that PLA can reach a 96% degree

Table 1

Advantages and limitations of 1.75 mm and 2.85 mm filaments.

Diameter	Advantages	Limitations	Typical Use Cases
1.75 mm	Industry standard, widely supported by most FDM printers; More precise extrusion control; Better for fine details and small nozzles (<0.4 mm); Easier to source and cheaper;	Lower maximum flow rate; Can be less stable in long Bowden tubes;	Desktop FDM printers, prototyping, detailed models, hobbyist application;
2.85 mm	Higher flow rate for faster and larger prints; Reduced risk of filament buckling in Bowden setups; Suitable for large-format or industrial printing;	Less common, fewer printer models support it; Slightly less precise for very fine details;	Professional or industrial printers, large-format parts, furniture, tooling, high-volume production.

of disintegration [17], thus meeting the 90% threshold required by EN 13432:2000. In controlled environments, complete decomposition may be achieved. However, in natural ecosystems (freshwater), PLA can persist for several years [18,19]. Due to its biocompatibility and safety, PLA is commonly used in nonstructural applications, including food containers, disposable packaging, and single use items.

2.1.2 Physical-mechanical characteristics of various printed parts

Table 2 presents the main physical and mechanical characteristics of various filaments used in FDM fabrication. The selection of appropriate filament should be guided by the specific functional requirements of the application:

- PLA is best suited for rigid, visually appealing prototypes and educational models.
- ABS or PC are more appropriate for components that require enhanced impact resistance and thermal stability.
- PETG and TPU are advantageous for applications that demand flexibility, chemical resistance, or moisture tolerance.
- Nylon offers an excellent compromise between mechanical strength and flexibility, ideal for load-bearing or moving parts.

2.2 New filaments

The continuous development of advanced composite filaments is one of the key drivers of FDM technology's expansion beyond prototyping into industrial and functional applications. Today, engineering-grade filaments such as PETG-CF (carbon fiber reinforced PETG), PAHT (high-temperature nylon), TPU (thermoplastic polyurethane), and PEEK (polyetheretherketone) are increasingly available for desktop and professional FDM printers. These materials offer significantly improved mechanical, thermal, and chemical resistance compared to standard PLA or ABS. For instance, PETG-CF achieves tensile strengths above 79 MPa [20], while PEEK exceeds 135 MPa compressive strength and withstands continuous temperatures over 250°C, making it suitable for aerospace, automotive, and medical-grade components [21,22]. TPE enables the creation of flexible, impact-resistant parts with elongation at break over 1000% [23].

Novel innovations include the integration of nanoparticles (e.g., graphene, carbon nanotubes) [24], conductive additives, and biodegradable compounds into FDM filaments [25,26]. In addition, metal-infused filaments constitute a significant class of 3D printing materials, merging the ease and versatility of thermoplastic extrusion with the enhanced mechanical and aesthetic properties of metals [27]. These filaments typically consist of a polymer matrix, such as PLA or ABS, embedded with finely powdered metal particles, enabling the fabrication of dense, metallic-like components using standard FDM technology. On the other hand, ceramic-filled filaments offer the distinct advantage of high-temperature resistance, making them well-suited for applications in the aerospace, automotive, and industrial sectors [28,29].

These developments will allow the

Table 2

Physical-mechanical properties of common filaments used in 3D printing.

Filament Type	Extrusion Temp. (°C)	Bed Temp. (°C)	Density (g/cm^3)	Tensile Strength (MPa)	Elongation at Break (%)	Elastic Modulus (MPa)	Typical Applications
PLA	190–210	60	1.25	50–65	8–10	2300–3600	Visual prototypes, educational models, decorative objects
ABS	220–260	90–110	1.05	45–50	8–22	2100–2400	Housings, technical parts, toys, automotive components
PETG	230–250	70–90	1.27	45–50	15–25	1800–2150	Moisture-resistant parts, guides
TPU (flexible)	200–230	40–60	1.20	35–50	300–450	750	Flexible soles, protective gear, gaskets, wristbands
Nylon	250–270	90–110	1.14	52–80	105–300	1680	Gears, wear-resistant parts, mechanical components
PC (Polycarbonate)	260–280	100–110	1.20	65–75	10–120	2300	Structural parts, headlights, thermal protection elements

fabrication of functional electronics, smart wearables, biosensors, and implantable devices directly from a desktop 3D printer. As these materials become more accessible and affordable, the applicability of FDM will significantly expand into sectors such as robotics, biomedicine, and electronics, accelerating the transition from prototyping to end-use manufacturing.

3. HOW FDM TECHNOLOGY IS RESHAPING DESIGN, PRODUCTION, AND EVERYDAY LIFE

In this section, several practical examples are highlighted, including some world-first achievements, to illustrate how FDM is transforming diverse industries, ranging from automotive to consumer products, and from orthopedic devices to drones.

3.1 Automotive

FDM has enabled the development of the first 3D-printed production vehicle, the Strati, created by Local Motors (Figure 4). This innovative car showcases how FDM technology can be applied not only for rapid prototyping but also for producing end-use automotive parts. The process takes 44 hours and allows for the customization of components such as brackets, mounts, handles, buttons, grilles, and various functional or aesthetic elements tailored to the specific requirements of each vehicle. FDM significantly reduces lead times and eliminates the need to maintain large inventories by enabling on-demand part fabrication. Technology also supports the creation of ergonomic accessories and user-specific enhancements for both interior and exterior applications.

The production of spare parts using 3D printing represents a significant innovation in the automotive sector, particularly for legacy and low-volume components. Porsche Classic, a division of the German automaker dedicated to vintage and discontinued models, has leveraged AM fabrication to address the challenges associated with sourcing rare spare parts. Many of these components are no longer mass-produced, and the original tooling required for traditional manufacturing methods is either unavailable or no longer functional. Recreating molds or dies for such parts would be economically unviable, especially given the low production volumes involved. To overcome these limitations, Porsche Classic has adopted on-demand 3D printing using both plastic and metal materials (Figure 5).

Fig. 4. Strati – the world's first car produced using FDM technology [30].

Fig. 5. Porsche printed spare parts for classic cars.

The Nera E-Bike, developed by BigRep, represents a pioneering demonstration of how large-format FDM can be pushed to fabricate functional mobility platforms almost entirely through 3D printing (Figure 6). Constructed with only 15 components, the Nera's frame, rims, airless tires, bumpers, seat, and external bodywork are manufactured using large-format BigRep printers. Multiple filaments were used to match structural and functional requirements such as: ProHT for rigid structural components (high temperature copolyester filament), PLA for colored detailing, PETG for transparent reflector parts, and TPU for flexible elements such as bumpers, handle grips, airless tires, and seat cushioning (Figure 6). The printed components were fabricated using nozzle diameters ranging from 0.6 mm to 1.0 mm, with layer heights between 0.4 mm and 0.6 mm. This configuration allowed for a balance between printing speed and structural integrity, particularly important for producing large-scale parts on industrial-grade FDM equipment.

Volkswagen successfully integrated desktop 3D printing into its manufacturing operations to reduce the cost and lead time associated with producing tools, jigs, and fixtures. Utilizing seven Ultimaker FDM printers, the plant now fabricates 93% of its tooling in-house, eliminating dependence on external suppliers and significantly enhancing production agility. Previously, outsourced tools involved long lead times, extensive documentation, and high costs. The shift to in-house additive manufacturing has shortened development cycles from several weeks to just hours. The cost savings are substantial. For example, to mount tires on the assembly line, operators use a wheel protection jig that was previously sourced for €800 but can now be 3D printed in-house for just €21 (Figure 7a). The development time for this tool has been reduced from 56 days to only 10 days. It is fabricated in approximately 30 hours using PLA and TPU filaments. Another example is the 2.0 TDI badge positioning jig, which previously cost €400 and required 35 days to produce. It is now printed in-house for just €10 in only 4 days (Figure 7b). Over a two-year period, Volkswagen achieved total savings of €475,000—averaging €325,000 per year—by avoiding tooling costs and streamlining production workflows. Beyond financial benefits, 3D printing has also enhanced ergonomics, tool customization, and quality control. Engineers can rapidly modify designs to meet operator needs, improving both workplace safety and assembly efficiency. Additionally, the digital workflow has reduced administrative overhead and enabled rapid prototyping, supporting continuous process improvement throughout the facility.

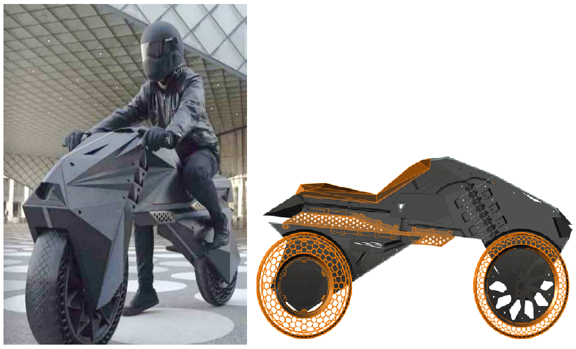

Fig. 6. World's first fully 3D Printed electric motorbike. Orange color marks the 3D Printed components from TPU filament [31].

Fig. 7. Printed tools used by Volkswagen in Autoeuropa plant from Portugal: a) Wheel protection jig, b) Support used to fix the 2.0 TDI logo on liftgate.

3.2 Drones

A newly developed jet-powered drone may be one of the most complex unmanned flying machines (UVA) ever built almost entirely using 3D printing technologies. Unveiled at the Dubai Airshow in 2016, the drone resembles a toy aircraft but features a 3-meter wingspan and an aerodynamically futuristic design (Figure 8). According to Aurora Flight Sciences and Stratasys, the companies behind the project, approximately 80% of its structure was designed and manufactured using 3D printing. The drone weighs only 15 kg and can reach speeds exceeding 241 km/h. To our knowledge, this is the largest, fastest, and most complex 3D-printed UAV built. The drone's design incorporates hollow internal structures, printed using FDM. These internal voids significantly reduce the drone's overall weight. Other components of the drone were printed using different AM technologies such as Selective Laser Sintering. Beyond technical complexity, 3D printing helped reduce the drone's design and manufacturing time by 50%, and the production cost was significantly lower compared to traditional methods (Figure 8). The project illustrates the growing potential of 3D printing for lightweight aerial vehicles, particularly drones.

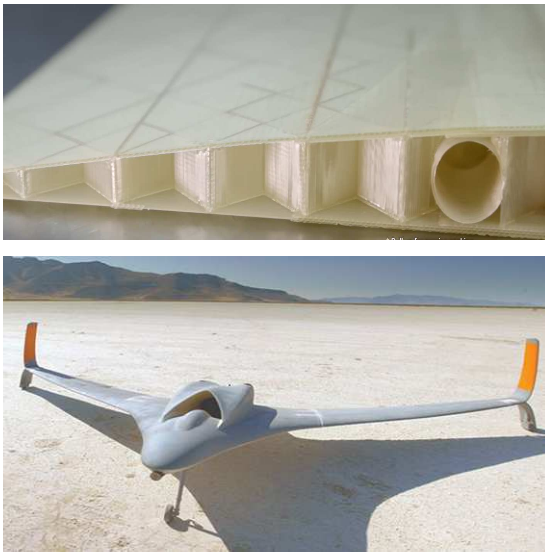

Fig. 8. World's first jet-powered, 3D printed UAV developed by Aurora Flight Sciences in collaboration with Stratasys [32].

Moreover, a 3D-printed UAV developed by engineers at the University of Southampton (UK) was successfully launched from a British naval vessel (HMS Mersey). The launch test of the SULSA drone is shown in Figure 9. The UAV, featuring a 1.2 m wingspan, can reach speeds of up to 97 km/h and operates with very low acoustic signature, making it particularly suitable for military reconnaissance and surveillance missions. The use of FDM technology significantly reduces development and production costs, allowing functional airframe components to be fabricated at a fraction of the cost associated with traditional composite manufacturing methods.

Fig. 9. World's first 3D printed aircraft automated launch from British naval ship HMS Mersey, developed by University of Southampton (UK).

3.3 Customized orthoses

The digitalization of medical manufacturing enables the production of personalized orthotic devices designed to replace traditional plaster casts used for immobilizing bone fractures (Figure 10a). The workflow integrates medical imaging, 3D scanning, CAD modeling, simulation, and FDM to produce ergonomic, lightweight, and reusable orthoses. The advantages of printed orthoses are:

►Lightweight and ergonomic: Considerably lighter than traditional plaster casts, improving patient comfort.

►Reusability and quick assembly: The orthosis can be easily mounted and removed for cleaning or examination.

►Enhanced hygiene and ventilation: The open structure design improves air circulation and allows regular skin hygiene, reducing the risk of irritation or infection.

Figure 10a presents a novel material and design approach for 3D-printed wrist-hand orthoses, highlighting advances in both structure and functionality. Figure 10b illustrates the BioNeek system, which is equipped with a shock absorber and an adjustable hinge, specifically engineered to support controlled joint motion and facilitate orthopedic rehabilitation. Steck et al. design and print an ankle–foot orthosis using fiber-reinforced filament type PETG-CF15 (Figure 10c). The workflow leverages 3D foot scanning to define anatomically accurate geometries, which are then optimized using topology-informed FEA under gait-specific loading conditions. By employing PETG-CF15, a polymer reinforced with 15% carbon fiber, the resulting orthoses achieve enhanced stiffness and structural stability while remaining suitable for FDM processing. The printing parameters were configured as follows: extruder temperature of 260 °C, bed temperature of 100 °C, infill print speed of 25 mm/s, 100% infill density, layer thickness of 0.2 mm, and a nozzle diameter of 0.6 mm (Figure 10c).

Fig. 10. Printed orthoses: a) Hand orthoses made of TPU and PLA [33], b) BioNeek system made of PEEK, c) Topology-optimized PETG-CF15 leg splint [34].

3.4 Shoes industry developments

To progress the shoes industry, it is critical to understand the biomechanical behavior of the human leg, and both theoretical and experimental studies have been extensively conducted in this field (Figure 11).

For example, Fodor and Arghir presented a comprehensive investigation of the biomechanical response of the human leg under vibration loading [35]. In their work, a four-degree-of-freedom (4-DOF) lumped-parameter biomechanical model of the human calf–foot system was proposed to analyze the dynamic mechanical behavior under external excitation The model represents the foot, tibia–fibula bone structure, calf muscle mass, and knee–femur segment as discrete masses interconnected through equivalent linear stiffness and damping elements, enabling the evaluation of load transmission through both bone and muscle pathways. The equations of motion for the biomechanical system were derived using d'Alembert's principle, leading to the matrix formulation (Eq. 1).

The system was solved using a fourth-order Runge–Kutta integration method implemented in the MATLAB environment, enabling time-domain evaluation of displacements, velocities, and accelerations of the biodynamic model [35]. After substituting the numerical values of mass, stiffness, and damping coefficients into the general dynamic formulation (Eq. 1), the system of motion equations is expressed in explicit numerical form as Eq. 2. This numerical formulation allows direct time-domain simulation of the biomechanical response of the calf–foot system under harmonic excitation. Each equation describes the acceleration of an anatomical segment as a function of external loading, viscous damping, and elastic restoring forces, with the coefficients reflecting the relative contribution of bone and muscle pathways to vibration transmission [35].

In the context of 3D-printed footwear and orthoses, this formulation provides a quantitative framework for evaluating how modifications in material stiffness and damping, achieved through FDM design parameters such as TPU selection, infill

Fodor and Arghir Eq. [35]

$$[M] \times \{\ddot{z}\} + [C] \times \{\dot{z}\} + [K] \times \{z\} = \{P\} \quad (1)$$

Where [M], [C], and [K] denote the mass, damping, and stiffness matrices, respectively, and P represents the external excitation vector.

$$\begin{cases} \ddot{z}_1 = 1.05(F_p - 1.31\dot{z}_1 + 0.46\dot{z}_2 - 440z_1 + 320z_2 + 70z_3) \\ \ddot{z}_2 - 1.96(0.46\dot{z}_1 - 1.5\dot{z}_2 + 1.047\dot{z}_4 + 320z_1 - 420z_2 + 100z_4) \\ \ddot{z}_3 = 0.39(0.46\dot{z}_1 - 1.5\dot{z}_2 + 1.047\dot{z}_4 + 70z_1 - 170z_3 + 100z_4) \\ \ddot{z}_4 = 0.30(1.047\dot{z}_2 + 1.047\dot{z}_3 - 2.094\dot{z}_4 + 100z_2 + 100z_3 - 200z_4) \end{cases} \quad (2)$$

Fig. 11. Biomechanical behavior of the human leg and foot.

density, and structural geometry, influence dynamic comfort, cushioning behavior, and vibration attenuation, thereby directly supporting the optimization of patient-specific orthopedic devices.

3.4.1 Novel shoe design and fabrication

A complementary and recent contribution is the collaborative study by the Massachusetts Institute of Technology (MIT) and Adidas, which further validates the integration of biomechanics, computation, and additive manufacturing in footwear design [36]. The 2024 research employed finite element analysis and optimal control–based biomechanical models to correlate runner kinematics with midsole stiffness, damping, and energy return. 3D Printed lattice structures were used to spatially tailor mechanical response along the sole (Figure 12).

Results demonstrated improved impact force attenuation, optimized energy storage–return behavior and reduced metabolic cost. In this context, the study provides strong technical validation for using AM-driven material gradients and lattice architectures in next-generation footwear and orthotic design. The MIT–Adidas study provides the scientific foundation for commercially available AM footwear platforms such as Adidas 4D, demonstrating how biomechanical modeling and lattice-based AM midsoles translate into real-world performance products (Figure 12).

Fig. 12. MIT–Adidas collaboration on modeling running via optimal control for shoe design, integrating biomechanical modeling and additive manufacturing, enabled midsole optimization [36].

3.4.2 Monomaterial shoes

Traditional footwear, particularly sneakers, often comprises over 60 individual components made from multiple materials [37]. These elements are typically bonded in ways that make separation for recycling economically impractical. As a result, most discarded shoes are shredded and incinerated, contributing to high consumption of primary raw materials. To address these challenges and promote sustainability in shoe manufacturing, FDM printing offers a promising alternative. This approach enables the production of monomaterial, customizable shoes, simplifying end-of-life recycling and reducing material waste throughout the product lifecycle.

A leading example is Zellerfeld, a German company founded in 2015. Zellerfeld offers fully 3D-printed, custom-fit shoes, produced without seams or adhesives (Figure 13). The company utilizes 3D foot scans to design each pair according to the user's unique anatomy. The shoes are printed entirely from thermoplastic polyurethane (TPU), valued for its flexibility and durability. Support structures are made from water-soluble material, allowing for easy removal during post-processing. This approach sustains a fully recyclable and circular production model, as each pair is made from a single, recyclable material. Zellerfeld operates over 200 printers, achieving a production time of approximately 24 hours per pair. The cost of these customized products ranges from $159 to $229.

Fig. 13. Customized sneakers, entirely printed from TPU by Zellerfeld without adhesives or stitching.

3.5 Aerial 3D printing

Zhang et al., recently published in Nature, presents a study focused on aerial 3D printing, a novel method in which autonomous aerial robots collaboratively fabricate structures directly in mid-air [38]. Inspired by natural builders like wasps, the system combines BuilDrones for material extrusion and ScanDrones for real-time quality monitoring. A scalable path planning and model predictive control framework adapts robot task allocation and fleet size based on geometric complexity.

The integration of a self-aligning delta manipulator improves deposition accuracy to approximately ±5 mm. They demonstrated scalable prints, validating the feasibility of in flight, unbounded AM (Figure 14).

A key innovation is the drone coordination and control, which creates a closed feedback loop by 3D scanning each deposited layer with an onboard RGB D sensor and adjusting the next toolpath accordingly. This real time correction enabled drones to adapt their trajectories on the fly, achieving accurate layer alignment with median errors of only 2.3 cm in a 2.05 m foam structure, marking the first demonstration of such feedback in aerial 3D printing (Figure 14).

Fig. 14. Drone coordination and control used for 3D printing [38].

4. CONCLUSION

FDM process part of AM has evolved from a prototyping method to a strategic production technology, enabling high-complexity, low-volume manufacturing across critical industries.

Filaments remain the cornerstone of 3D printing, offering a diverse and rapidly expanding material base that enables both prototyping and functional part fabrication. Filaments such as PLA, ABS, PETG, TPU, and carbon fiber-reinforced polymers continue to dominate the AM market due to their accessibility, improved mechanical strength, heat resistance, chemical durability, and even biocompatibility, thus extending their applicability from hobbyist use to automotive, medical, aerospace, industrial tooling, and mass products.

From a sustainability perspective, FDM enables material reuse and waste reduction, achieving up to 70% savings.

In 10 years, FDM is expected to cover 40–50% of desktop AM, with advanced materials, integrated recycling, and automated post-processing.

5. REFERENCES

[1] Hull, C.W. *Apparatus for Production of Three-Dimensional Objects by Stereolithography*. U.S. Patent US4575330A, 11 March 1986.

[2] Gebhardt, A.; Kessler, J.; Thurn, L. *3D Printing: Understanding Additive Manufacturing, 2nd ed.*; Carl Hanser Verlag GmbH: Munich, Germany, 2019; pp. 1–220; ISBN 978-1-56990-702-3.

[3] Takagishi, K.; Umezu, S. Development of the Improving Process for the 3D Printed Structure. *Nature Sci. Rep*. 2017, *7*, 39852.

[4] Uriciuc, W.A.; Vermesan, H.; Tiuc, A.E.; Ilea, A.; Bosca, A.B.; Popa, C.O. Casting over Metal Method Used in Manufacturing Hybrid Cobalt-Chromium Dental Prosthetic Frameworks Assembles. *Materials* 2021, *14*, 539.

[5] Cosma, C.; Moldovan, M.; Simion, M.; Balc, N. Impact of laser parameters on additively manufactured cobalt-chromium restorations. *Journal Prosthetic Dentistry* 2021, *128*, 421–429.

[6] Panico, A.; Corvi, A.; Collini, L.; Sciancalepore, C. Multi objective optimization of FDM 3D printing parameters set via design of experiments and machine learning algorithms. *Nature Scientific Reports* 2025, 15 (1).

[7] Gao, G.; Xu, F.; Xu, J.; Tang, G.; Liu, Z. A Survey of the Influence of Process Parameters on Mechanical Properties of Fused Deposition Modeling Parts. *Micromachines* 2022, *13*, 553.

[8] Mazurchevici, S.N.; Mazurchevici, A.D.; Nedelcu, D. Dynamical Mechanical and Thermal Analyses of Biodegradable Raw Materials for Additive Manufacturing. *Materials* 2020, *13*, 1819.

[9] Comes, R.; Neamțu, C. Design a low-cost eyewear display adapted to additive manufacturing. *Acta Technica Napocensis,* 2015, *58* (4).

[10] Monkova, K.; Monka, P.P.; Burgerova, J.; Szabo, G. Investigating the Flexural Properties of 3D-Printed Nylon CF12 with Respect to the Correlation Between Loading and Layering Directions. *Polymers* 2025, *17*, 788.

[11] Crump, S. Scott. *Apparatus and Method for Creating Three-Dimensional Objects*; U.S. Patent US 5,121,329 A, filed 30 October 1989, granted 9 June 1992; assigned to Stratasys, Inc.

[12] Chirilă Băbău, A.M.; Micle, V.; Damian, G.E.; Sur I.M. Lead and copper removal from sterile dumps by phytoremediation with Robinia pseudoacacia. *Nature Sci Rep* 2024, *14*, 9842.

[13] Florean, C.T.; Vermesan, H.; Thalmaier, G.; Neamtu, B.V.; Gabor, T.; Campian, C.; Hegyi, A.; Csapai, A. The Influence of TiO_2 Nanoparticles on the Physico–Mechanical and Structural Characteristics of Cementitious Materials. *Coatings* 2024, *14*, 218.

[14] Torka, B. *BMW Group, Turning Old into New: Recycling as Next Step towards Greater Circular Economy for BMW Group 3D Printing*. BMW Group Press Release 2025. Available online: https://www.press.bmwgroup.com/global/article/detail/T0451410EN?language=en (accessed on 30 July 2025).

[15] Avery, S. *Sustainability Meets Style with Zellerfeld and Moncler's 3D Printed Trailgrip Sneaker*. 3Dnatives 2023. Available online: www.3dnatives.com/en/moncler-zellerfeld-3d-printed-sneaker0707234.

[16] Maragkaki, A.; Malliaros, N.G.; Sampathianakis, I.; Lolos, T.; Tsompanidis, C.; Manios, T. Evaluation of Biodegradability of Polylactic Acid and Compostable Bags from Food Waste under Industrial Composting. *Sustainability* 2023, *15*, 15963.

[17] Intaraksa, P.; Rudeekit, Y.; Siriyota, P.; Leejarkpai, T. Comparative Study of the Bio-Disintegration Behavior of Polylactic Acid under Laboratory and Pilot-Scale Composting Conditions. *Advanced Materials Research* 2013, *747*, 678–681.

[18] Hajilou, N.; Mostafayi, S.S.; Yarin, A.L.; Shokuhfar, T. A Comparative Review on Biodegradation of Poly(Lactic Acid) in Soil, Compost, Water, and Wastewater Environments: Incorporating Mathematical Modeling Perspectives. *AppliedChem* 2025, *5*, 1.

[19] Krasowska, K.; Heimowska, A. Degradability of Polylactide in Natural Aqueous Environments. *Water* 2023, *15*, 198.

[20] Valvez, S.; Silva, A.P.; Reis, P.N.B. Optimization of Printing Parameters to Maximize the Mechanical Properties of 3D-Printed PETG-Based Parts. *Polymers* 2022, *14*, 2564.

[21] Moby, V.; Dupagne, L.; Fouquet, V.; Attal, J.-P.; François, P. Mechanical Properties of Fused Deposition Modeling of Polyetheretherketone (PEEK) and Interest for Dental Restorations: A Systematic Review. *Materials* 2022, *15*, 6801.

[22] Abbas, K.; Hedwig, L.; Balc, N.; Bremen, S. Advanced FFF of PEEK: Infill Strategies and Material Characteristics for Rapid Tooling. *Polymers* 2023, *15*, 4293.

[23] Gregory, G. L.; Sulley, G. S.; Carrodeguas, L. P.; Chen, T. T. D.; et al. Triblock polyester thermoplastic elastomers with semi-aromatic polymer end blocks by ring-opening copolymerization. *Chemical Science* 2020, *11* (25), 6567–6581.

[24] Blyweert, P.; Nicolas, V.; Fierro, V.; Celzard, A. 3D Printing of Carbon-Based Materials: A *Review. Carbon* 2021, *183*, 449–485.

[25] Samir, A.; Ashour, F. H.; Hakim, A. a. A.; Bassyouni, M. Recent advances in biodegradable polymers for sustainable applications. *Nature Materials Degradation* 2022, *6* (1).

[26] Ahmad, M.N.; Ishak, M.R.; Mohammad Taha, M.; Mustapha, F.; Leman, Z. A Review of Natural Fiber-Based Filaments for 3D Printing: Filament Fabrication and Characterization. *Materials* 2023, *16*, 4052.

[27] Martin, V.; Witz, J.-F.; Gillon, F.; Najjar, D.; Quaegebeur, P.; et al. Low Cost 3D Printing of Metals Using Filled Polymer Pellets. *HardwareX* 2022, *11*, e00292.

[28] Kantaros, A.; Soulis, E.; Petrescu, F.I.T.; Ganetsos, T. Advanced Composite Materials Utilized in FDM/FFF 3D Printing Manufacturing Processes: The Case of Filled Filaments. *Materials* 2023, *16*, 6210.

[29] Avram, S.E.; Birle, B.V.; Cosma, C.; Tudoran, L.B.; Moldovan, M.; Cuc, S.; Borodi, G.; Petean, I. Ecological Building Material Obtained Through the Moderate Thermal Consolidation of Ceramic Slurry Collected from Industrial Waste Waters. *Materials* 2025, *18*, 1715.

[30] Russon, M.-A. *The Strati: World's First 3D-Printed Electric Car Built in Just 44 Hours*; Int Business Times, London, UK, 2014. Available online: accessed on 8 May 2025. www.ibtimes.co.uk/strati-worlds-first-3d-printed-electric-car-built-just-44-hours-1465706.

[31] BigRep. *NERA E-Motorbike: The First Fully 3D-Printed Electric Motorcycle*; BigRep GmbH: Berlin, Germany, 2018. Available online: accessed on 28 July 2025. https://bigrep.com/nera-e-motorbike.

[32] Aurora Flight Sciences. *Stratasys Partners with Aurora Flight Sciences to Design and Develop the World's First 3D-Printed Jet-Powered Aircraft*; Stratasys Ltd. USA. Available online: accessed on 1 July 2025 www.stratasys.com/en/resources/case-studies/aurora.

[33] Popescu, D.; Iacob, M.C.; Tarbă, C.; Lăptoiu, D.; Cotruţ, C.M. Exploring a Novel Material and Approach in 3D-Printed Wrist-Hand Orthoses. *J. Manuf. Mater. Process.* 2024, *8*, 29.

[34] Steck, P.; Scherb, D.; Witzgall, C.; Miehling, J.; Wartzack, S. Design and Additive Manufacturing of a Passive Ankle–Foot Orthosis Incorporating Material Characterization for Fiber-Reinforced PETG-CF15. *Materials* 2023, *16*, 3503.

[35] Fodor, R.Ș.; Arghir, M. Contributions to the Biomechanics Study of Human Calf Foot. *Acta Technica Napocensis* 2015, *58*, 571–580.

[36] Fay, S.C.; Hosoi, A.E. Modeling Running via Optimal Control for Shoe Design. *J. Biomech. Eng.* 2024, *146*, 041004.

[37] Trapp, M.; Kreutz, M.; Lütjen, M.; Freitag, M. Improving sustainability of footwear production through 3D printing of shoes. *In Digitization of the work environment for sustainable production*; 2022; pp 1–15.

[38] Zhang, K., Chermprayong, P., Xiao, F. et al. Aerial additive manufacturing with multiple autonomous robots. *Nature* 2022, *609*, 709–717.

Personalizare și sustenabilitate prin imprimare 3D: Aplicații de la industria auto la produse de larg consum

Rezumat: Această lucrare prezintă o analiză a tehnologiei Fused Deposition Modeling (FDM), urmărind evoluția sa de la primul brevet până la adoptarea pe scară largă ca tehnologie de bază în fabricația aditivă. Sunt analizate principiul de funcționare, avantajele și limitările procesului, cu accent pe eficiența costurilor și libertatea de proiectare. Studiul examinează cele mai utilizate filamente (PLA, ABS, PETG, TPU și Nylon), alături de materiale ranforsate precum PETG-CF, menționându-se caracteristicile lor fizico-mecanice și potențiale aplicații. Câteva premiere internaționale sunt prezentate cum ar fi primul autovehicul printat 3D, prima motocicletă electrică și prima dronă cu propulsie prin reacție. Din punct de vedere al sustenabilității, procesul FDM permite reutilizarea materialelor și reducerea deșeurilor, realizând economii de până la 70%. Studii de caz din domeniul auto (Volkswagen, BMW), drone militare (Marina Britanică), dispozitive medicale ortopedice (BioNeek) și încălțăminte (MIT–Adidas, Zellerfeld), demonstrează rolul tot mai important al fabricației FDM în personalizarea de masă în diverse sectoare.

Marinela COSMA, PhD student, Technical University of Cluj-Napoca, Faculty of Materials and Environmental Engineering, 400641 Cluj-Napoca, Romania, marinela.petrut@campus.utcluj.ro. Phone +40755851025. EUt+ Research Institute/Group, European University of Technology, European Union.

Horațiu VERMEȘAN, Prof. Dr. Eng., Technical University of Cluj-Napoca, Faculty of Materials and Environmental Engineering, 400641 Cluj-Napoca, Romania, horatiu.vermesan@imadd.utcluj.ro. EUt+ Research Institute/Group, European University of Technology, European Union.