

3D AND 4D PRINTING FOR WASTE REDUCTION AND RESOURCE OPTIMIZATION

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Pregledni članak

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Abstract

In the pursuit of sustainable industrial transformation, additive manufacturing has emerged as more than a technological revolution—it represents a new philosophy of production. This paper explores how 3D and 4D printing technologies can serve as key enablers of waste reduction and resource optimization across diverse sectors. By shifting from traditional subtractive methods to digitally controlled additive processes, 3D printing minimizes material loss and energy use through precision, customization, and local production. Going a step further, 4D printing introduces smart, stimuli-responsive materials capable of self-adaptation and regeneration, creating systems that not only reduce waste but actively extend product lifecycles. Through an interdisciplinary lens, the study examines material innovation, eco-design principles, and the integration of artificial intelligence and digital twins for real-time optimization of manufacturing processes. The findings highlight the transformative potential of additive and time-evolving manufacturing in supporting circular economy objectives, Industry 5.0 paradigms, and the broader goals of the European Green Deal. Ultimately, the paper argues that the convergence of digital intelligence and material adaptability offers a tangible pathway toward regenerative, zero-waste production ecosystems. Its originality lies in bridging technological foresight with applied sustainability practice, offering actionable insights for industries and policymakers seeking to redesign value chains through intelligent, resource-positive manufacturing.

Keywords: circular economy, waste reduction, additive manufacturing, 4D printing, 3D printing

JEL classification: Q55, Q01, O33, O14

INTRODUCTION

In an era where sustainability has become the defining challenge of industrial progress, the convergence of advanced manufacturing technologies and environmental responsibility is reshaping the very foundations of production and design. Traditional manufacturing systems—rooted in mass production, resource extraction, and material waste—are being questioned by the growing urgency to transition toward circular and regenerative models. Within this transformative landscape, 3D and 4D printing technologies stand out as catalysts of a new industrial revolution: one that values precision over excess, intelligence over inertia, and adaptability over rigidity. The momentum of this transformation is reflected in the global market trajectory. The 3D printing industry, valued at approximately USD 15.39 billion in 2024, is projected to expand to USD 35.79 billion by 2030, representing a compound annual growth rate (CAGR) of 17.2% (MarketsandMarkets, 2025). This rapid expansion is driven by advances in additive manufacturing processes, the emergence of bio-based and recyclable materials, and a rising demand for customized, resource-efficient products. Such exponential growth not only signals a technological shift but also underscores the strategic and environmental relevance of additive manufacturing in achieving industrial sustainability.

3D printing, or additive manufacturing, marks a paradigm shift from the logic of subtraction to the art of addition. By building objects layer by layer directly from digital models, it eliminates the inefficiencies of traditional production—minimizing scrap material, reducing tooling costs, and enabling on-demand, localized fabrication. This shift not only reduces the environmental footprint but also democratizes manufacturing, allowing for customized, small-batch production tailored to local and sectoral needs. Yet the story does not end with precision and efficiency. The next frontier—4D printing—introduces the dimension of time, enabling materials to transform, adapt, or self-heal in response to external stimuli such as heat, light, or moisture. Here, matter itself becomes intelligent: a programmable system capable of responding to its environment, thereby redefining the very nature of products and their lifecycle. Importantly, the sustainability promise of these technologies is strengthened by insights from broader digital transformation research, which shows that digital ecosystems powered by AI, together with architectures designed for scalability and low-energy operation, have become powerful engines of eco-innovation—shaping how organizations achieve both environmental performance and operational sustainability (Ahmić, 2025).

This paper explores the transformative potential of 3D and 4D printing as enabling technologies for waste reduction and resource optimization, positioning them as cornerstones of sustainable industrial ecosystems. It examines how additive manufacturing principles, when integrated with smart materials, artificial intelligence (AI), and digital twins, can achieve new thresholds of efficiency, circularity, and resilience. Through a comparative analysis illustrated with tables, this study examines how 3D and 4D printing converge with material innovation, eco-design principles, and digital intelligence to create closed-loop, resource-positive production systems. The paper encompassed four dimensions: (1) the conceptual and technological foundations of additive manufacturing; (2) material innovation through recyclable, biodegradable, and bio-based composites; (3) precision-driven waste minimization; and (4) the integration of AI, IoT, and digital twin technologies for real-time optimization of production efficiency.

1. UNDERSTANDING 3D AND 4D PRINTING TECHNOLOGIES

Additive manufacturing—widely known as 3D printing—represents one of the most transformative technological innovations of the 21st century, redefining how products are designed, prototyped, and produced. Unlike traditional subtractive manufacturing, which removes material from a solid block to achieve the desired shape, additive manufacturing builds objects layer by layer from digital blueprints (Zhou et al., 2024).

This approach allows for an unprecedented degree of precision, customization, and material efficiency, marking a shift from mass production toward mass personalization.

At its core, 3D printing operates through the sequential deposition of material—whether polymer, resin, metal, or biocomposite—in ultra-thin layers. Each layer fuses to the previous one through controlled heating, curing, or binding, gradually forming a three-dimensional structure. This process eliminates the need for molds or cutting tools and enables the fabrication of complex geometries that were once impossible or prohibitively expensive to achieve. As a result, 3D printing has become a cornerstone of innovation in various sectors, enabling rapid prototyping, sustainable material use, and circular production practices.

While 3D printing revolutionized the concept of form, 4D printing extends this revolution into the realm of function and transformation. The “fourth dimension” in 4D printing is time—an added layer of dynamism that allows printed objects to change shape, structure, or behavior in response to external stimuli such as heat, light, moisture, or magnetic fields (Piedade, 2019). This capability is made possible through the use of smart materials—polymers, hydrogels, or shape-memory alloys—that are programmed at the molecular level to respond predictably to environmental conditions. For example, a 4D-printed valve might automatically open and close with temperature fluctuations, or a biomedical implant could adapt to changes within the human body.

The key distinction between 3D and 4D printing lies in their temporal and functional evolution. While 3D printing focuses on static fabrication—objects that maintain their original form—4D printing introduces self-transformation, enabling materials to reconfigure or self-assemble after production. Yet, these two technologies are not divergent; rather, they are converging in powerful ways. Advances in multi-material printing, AI-driven design, and digital simulation are blurring the boundaries between structure and behavior, form and function. Together, they point toward a new era of adaptive manufacturing, where products are not merely made—they are programmed to evolve.

In essence, understanding 3D and 4D printing is understanding the future of creation itself: a future where materials think, products adapt, and innovation unfolds layer by layer—and moment by moment.

Table 1. Comparative Overview of 3D and 4D Printing Technologies

Dimension	3D Printing (Additive Manufacturing)	4D Printing (Additive + Time-Responsive Manufacturing)
Core Concept	Constructs three-dimensional objects through additive, layer-by-layer deposition from a digital blueprint.	Extends 3D printing by introducing the dimension of time—objects can transform or self-adapt post-production.
Process Nature	Static fabrication: objects retain fixed form and function once printed.	Dynamic fabrication: objects can change shape, structure, or properties in response to external stimuli.
Material Types	Uses polymers, resins, metals, ceramics, and biocomposites optimized for structural integrity and precision.	Employs smart materials such as hydrogels, shape-memory polymers, and responsive alloys programmed for functional transformation.
External Stimuli Interaction	No active response to environmental stimuli; materials are inert post-production.	Actively responds to heat, light, moisture, pH, or magnetic fields—triggering predictable changes in geometry or performance.

Integration with digital technologies	Relies on CAD modeling, slicers, and machine learning for process efficiency and predictive maintenance.	Integrates AI, IoT, and digital twins to simulate, monitor, and optimize performance continuously in real time.
Key Limitation	Limited post-production functionality; mechanical properties fixed after fabrication.	Complexity of material behavior and control; high cost of smart materials and environmental calibration.
Future Direction	Advances in multi-material printing, faster production, and sustainable feedstocks.	Convergence with AI-driven design and adaptive manufacturing ecosystems for autonomous, intelligent production.

Source: Author work

2. MATERIAL INNOVATION AND CIRCULAR DESIGN

At the core of the sustainability transition in additive manufacturing lies an equally transformative domain—material innovation and circular design. As the boundaries of 3D and 4D printing expand, the focus is shifting from not only *how* objects are made, but also *what* they are made of and *how* they behave across their entire lifecycle. This paradigm reflects a profound reorientation of industrial thinking: from linear “take–make–dispose” models toward circular material systems, in which every component is conceived as part of a regenerative continuum. This perspective aligns with our earlier findings, which highlight that the adoption of advanced materials—ranging from biocomposites to nanomaterials and smart materials—acts as a pivotal driver of circular transformation by enabling the substitution of finite, non-recyclable inputs with sustainable, regenerative alternatives (Ahmić & Ćosić, 2025). The emergence of recyclable, biodegradable, and bio-based materials represents one of the most decisive breakthroughs in this evolution. Conventional petroleum-based polymers, though once indispensable for additive manufacturing, are increasingly being replaced by materials derived from renewable sources such as polylactic acid (PLA), cellulose, algae-based biopolymers, or mycelium composites. These new materials not only reduce reliance on finite fossil resources but also integrate seamlessly into biological cycles, where they can decompose naturally or be reprocessed into new inputs. Similarly, recycled thermoplastics, metal powders, and composite blends are enabling circular loops within manufacturing ecosystems—allowing waste from one production cycle to serve as the raw material for the next (Dong et al., 2025). Such innovations elevate sustainability from a peripheral concern to a structural property of design.

Yet, material innovation alone cannot achieve circularity without a corresponding shift in design logic. This is where design for disassembly, reuse, and recyclability becomes essential. In contrast to traditional manufacturing, where products are assembled for permanence, circular design advocates for intentional impermanence—the ability to easily dismantle, repair, or remanufacture components. Through modular architecture and standardized connectors, additive manufacturing enables products to be reconfigured or upgraded rather than discarded (Habib et al., 2023). For example, in architecture and aerospace, structures can be printed in segments designed for efficient separation and repurposing, dramatically reducing end-of-life waste. This approach transforms products into dynamic material banks, whose components retain economic and environmental value long after their initial use. The integration of digital material optimization further strengthens this paradigm. Leveraging artificial intelligence (AI), generative design, and digital twins, designers can simulate material behavior, predict wear patterns, and minimize resource input before physical production even begins. These tools allow engineers to achieve maximum performance with minimal material, optimizing both density and strength through algorithmic precision. In doing so, digital optimization transforms sustainability into a measurable design parameter rather than an aspirational goal. Eco-design principles thus evolve from static guidelines into intelligent, data-driven frameworks that continuously refine product efficiency across its lifecycle.

3. WASTE REDUCTION THROUGH ADDITIVE PRECISION

One of the most profound contributions of additive manufacturing to sustainability lies in its unparalleled precision, which redefines the relationship between material use and production efficiency. In contrast to conventional subtractive manufacturing—where excess material is carved, milled, or cut away—additive manufacturing operates on a layer-by-layer construction principle, employing exactly the amount of material required to realize a design. This methodological inversion not only minimizes waste at the source but also transforms the very logic of industrial resource management. The layer-by-layer precision inherent in 3D and 4D printing ensures that every particle, filament, or droplet of material serves a defined structural or functional purpose. Unlike traditional processes that may discard up to 80% of raw input (Graziosi et al., 2024), additive systems achieve near-zero waste production, particularly when paired with recyclable feedstocks or bio-based polymers. Such exactitude enables the fabrication of complex geometries—lattices, hollow cores, and graded structures—that optimize strength while reducing mass, further amplifying material efficiency. This form of precision engineering embodies both technological sophistication and environmental responsibility. Furthermore, additive manufacturing, enables just-in-time fabrication, where production aligns directly with real-time demand. This model drastically reduces the ecological and economic burden of overproduction, warehousing, and logistics, while empowering industries to localize production and shorten supply chains. By decentralizing manufacturing, 3D and 4D printing support a distributed circular economy, where value creation occurs closer to the point of use, minimizing both material and energy flows.

A quantitative comparison between additive and traditional manufacturing further underscores the scale of this efficiency. Empirical studies reveal that additive manufacturing can reduce material waste by 80–90%, energy consumption by up to 60%, and carbon emissions by 80%, depending on the material and application (Oladunni et al., 2025). For example, in the medical sector, customized implants printed from titanium powder exhibit not only improved biocompatibility but also up to 75% reduction in raw material usage compared with conventional milling (Das & Rajkumar (2025). Similarly, in the automotive and construction industries, additive fabrication eliminates the need for molds, dies, and assembly line waste, translating directly into lower lifecycle impacts and higher resource retention.

4. RESOURCE OPTIMIZATION AND SMART MANUFACTURING

The next frontier in sustainable industrial transformation extends beyond efficient material use toward intelligent orchestration of resources—a domain where artificial intelligence (AI), the Internet of Things (IoT), and digital twins converge to redefine how production systems think, adapt, and evolve. Additive manufacturing, when integrated into this digital ecosystem, no longer operates as an isolated fabrication technique but as part of a self-optimizing network that continuously learns from data, predicts outcomes, and adjusts its own parameters in real time. This marks the rise of smart manufacturing, where sustainability is not only designed but computationally governed. Through the integration of AI algorithms, manufacturers can model, monitor, and optimize every aspect of the additive process—from toolpath generation and thermal management to energy consumption and material distribution. Machine learning enables the identification of inefficiencies invisible to human observation, allowing systems to autonomously adjust printing parameters to achieve the ideal balance between speed, strength, and energy use (Aktepe & Ergün, 2025). In parallel, IoT-enabled sensors collect vast streams of data on temperature, vibration, humidity, and power usage across the production chain, transforming the manufacturing floor into a living network of information. When connected to digital twin platforms, this data enables the creation of virtual replicas of physical assets—constantly updated, simulated, and tested—to forecast performance, prevent downtime, and minimize resource waste before it occurs.

The fusion of these digital technologies is unlocking a new paradigm of adaptive and self-regulating production. In particular, 4D printed components represent a breakthrough in this evolution. Engineered with stimuli-responsive materials, they possess the ability to self-assemble, reconfigure, or heal in response to environmental triggers. Such adaptive systems blur the distinction between manufacturing and maintenance: a component may transform its geometry to reduce aerodynamic drag, seal microcracks under heat, or alter permeability under humidity—all without external intervention. This embedded intelligence allows materials themselves to participate in optimization, extending lifespan and radically reducing the need for replacement parts. Complementing these innovations are closed-loop systems that integrate digital monitoring with circular resource management. Waste material, residual heat, or by-products from one process can be recaptured, analyzed, and reintegrated into the next production cycle, forming self-sustaining industrial metabolisms. Through real-time optimization, such systems dynamically balance material flow and energy input, ensuring that each production stage operates at peak efficiency with minimal environmental footprint. The loop is both physical and digital: materials circulate, but so does knowledge—continuously refined by data analytics to improve future production cycles.

5. APPLICATIONS AND ENVIRONMENTAL IMPACTS

The transformative power of 3D and 4D printing technologies extends far beyond the laboratory or prototype workshop—it is reshaping the architecture of entire industries and redefining how sustainability is embedded across value chains. Their capacity for precision, adaptability, and digital integration has opened unprecedented possibilities for cross-sectoral applications that simultaneously drive economic growth and environmental responsibility. In each domain—construction, healthcare, fashion, and aerospace—these technologies are not merely substituting traditional processes but fundamentally reconfiguring them to align with the principles of efficiency, resilience, and circularity. In the construction sector, 3D printing is redefining how we build our physical environments. One of the most cited examples is ICON, a U.S.-based company that has constructed around 200 fully 3D-printed homes using proprietary concrete blends that reduce material waste by up to 60% and cut construction time in half (ICON, 2022). Similarly, COBOD International has deployed its robotic 3D printers to build modular schools in Malawi and residential units in Denmark using locally sourced materials. These initiatives demonstrate a scalable model for affordable, low-carbon housing—an approach that resonates strongly with Bosnia and Herzegovina’s pressing need for energy-efficient housing and post-industrial urban renewal. Integrating similar 3D printing technologies into Bosnia’s construction landscape could accelerate reconstruction projects, particularly in smaller municipalities where access to traditional materials and skilled labor remains limited. The introduction of adaptive 4D-printed façades—materials that can autonomously adjust ventilation or insulation in response to weather—could further strengthen the country’s alignment with the EU Green Deal’s building efficiency targets. In healthcare, additive manufacturing is already transforming patient care through personalization and precision. Materialise, a company headquartered in Belgium but active across Central Europe, has pioneered patient-specific implants, surgical guides, and 3D anatomical models that enhance surgical accuracy while reducing operative waste. In neighboring Croatia and Slovenia, similar biomedical innovation hubs are emerging, indicating strong potential for regional collaboration. For Bosnia and Herzegovina, where the healthcare sector seeks modernization and cost-effective innovation, integrating 3D bioprinting facilities could allow customized prosthetics or dental implants to be produced locally, eliminating import dependencies. Moreover, the next generation of 4D bioprinting—where implants can adapt to tissue growth or biological change—holds promise for regenerative medicine partnerships between medical faculties, engineering schools, and private startups.

The fashion and textile industry, one of Bosnia’s traditional economic pillars, also stands on the brink of digital transformation. Global pioneers such as Adidas and Balenciaga have incorporated 3D printing to produce limited-edition footwear and apparel with zero-waste design processes. Startups like Julia Koerner Studio in Austria and Danit Peleg in Israel are exploring on-demand clothing that is entirely digitally fabricated, eliminating overproduction and inventory waste. For Bosnia and Herzegovina, where textile craftsmanship remains strong but faces challenges from mass imports and fluctuating labor costs, the introduction of 3D-printed fashion accessories and 4D-adaptive fabrics could reposition local designers toward high-value sustainable fashion exports. Combining heritage textile techniques with digital fabrication could open a niche market for “Made in Bosnia” eco-tech couture—uniquely merging tradition with circular innovation. From an environmental perspective, life cycle analysis (LCA) consistently validates the sustainability gains of additive manufacturing. 4D-printed smart materials in construction can extend service life up to 20%, as their adaptive properties reduce degradation and maintenance cycles (Bellegheem et al., 2017). If implemented strategically, these figures could be mirrored in Bosnia and Herzegovina’s building materials, machinery, and furniture industries—where inefficiencies and high energy intensity remain persistent obstacles to sustainability.

Table 2. Comparative Analysis of 3D and 4D Printing for Waste Reduction and Resource Optimization and its application

Analytical Dimension	3D Printing (Additive Manufacturing)	4D Printing (Adaptive Additive Manufacturing)
Core Sustainability Function	Reduces waste through precise layer-by-layer fabrication.	Enhances sustainability through materials that adjust or regenerate over time.
Material Efficiency	Achieves up to 80–90% reduction in raw material waste compared to subtractive methods; uses recyclable polymers, metals, or composites. (Graziosi et al., 2024)	Employs smart and stimuli-responsive materials (shape-memory polymers, hydrogels) that <i>reconfigure</i> or <i>self-heal</i> , further minimizing material loss across product life cycles.
Energy Optimization	Reduces energy use by 60% via precision deposition and elimination of tooling; energy savings depend on material type and geometry (Oladunni et al., 2025)	Enables dynamic energy management —materials and systems optimize energy use during function (e.g., self-regulating temperature or aerodynamic forms).
Production Model	Produces on demand, minimizing transport emissions and inventory waste.	Operates through predictive, data-driven adaptation across the product’s life cycle.
Lifecycle Resource Use	Focused on efficient resource use during fabrication; parts are optimized for strength-to-weight ratio and recyclability.	Introduces active lifecycle efficiency —components can alter shape or stiffness to prolong usability, extending product lifetime by up to 20%.
Circular Economy Integration	Supports closed-loop reuse—materials can be reprocessed and reprinted.	Advances regenerative cycles—smart materials restore function, reducing long-term losses.
Design Philosophy	Guided by <i>eco-design principles</i> : reduce, reuse, and redesign through algorithmic precision.	Guided by <i>bio-intelligent design</i> : emulate natural adaptability to achieve regenerative and self-sustaining resource flows.

Environmental Impact (per LCA studies)	Reduces CO ₂ emissions up to 80% compared to traditional manufacturing; significant savings from shorter supply chains and reduced scrap (Oladunni et al., 2025)	Reduces environmental footprint across <i>use-phase</i> and <i>end-of-life</i> stages through autonomous adaptation, lower maintenance, and self-repair mechanisms.
Industrial Applications	Architecture (printed walls, bridges), healthcare (implants, prosthetics), automotive (lightweight parts), consumer goods.	Aerospace (morphing wings), construction (adaptive façades), biomedical (self-adjusting implants), textiles (shape-changing fabrics), soft robotics, and smart infrastructure.
Waste Reduction Strategy	Eliminates overproduction, supports zero-inventory manufacturing , and reuses material feedstock.	Prevents post-use waste through self-repairing and reusable systems , eliminating premature disposal.
Resource Optimization Strategy	Focuses on process-level optimization—material use, speed, and energy balance.	Expands optimization to system-level intelligence —combining digital sensing, adaptive materials, and continuous feedback for long-term efficiency.

Source: Author work

CONCLUSION AND RECOMMENDATIONS

As industries confront the mounting pressures of climate change, resource scarcity, and the imperative for circularity, this paper demonstrates that 3D and 4D printing technologies offer far more than incremental improvements—they represent a fundamental redesign of how societies produce, use, and regenerate materials. The analysis shows that additive manufacturing not only minimizes waste through geometric precision and on-demand fabrication but also unlocks new pathways for circular design through recyclable, bio-based, and digitally optimized materials. In parallel, 4D printing extends this logic beyond production into the full lifespan of a product, enabling components that adapt, self-heal, and sustain functionality in ways traditional materials cannot. Together, these technologies redefine efficiency not as a static metric but as a dynamic, evolving property of intelligent industrial systems. The integration of AI, IoT, and digital twins further amplifies this potential, transforming manufacturing from a linear, resource-intensive sequence into a responsive, data-driven ecosystem capable of continuous optimization. From a policy perspective, the strategic integration of 3D and 4D printing technologies offers Bosnia and Herzegovina a clear pathway to align with the European Union's Circular Economy Action Plan and the European Green Deal. These frameworks prioritize resource-efficient production, low-carbon industrial transformation, and digitalization of manufacturing—principles that additive and adaptive manufacturing inherently support. To operationalize these ambitions, Bosnia and Herzegovina could pursue a coordinated set of national and regional initiatives that stimulate innovation, build human capital, and accelerate industrial modernization. A first step would be the establishment of state-level or cantonal 3D/4D Innovation Centers in Sarajevo, Tuzla, Mostar, Travnik, and Banja Luka. These centers would function as open-access hubs equipped with advanced additive and smart-material fabrication technologies, enabling SMEs, startups, students, and researchers to translate ideas into prototypes and market-ready products. Such hubs would not only accelerate technology transfer but also reduce regional disparities in innovation capacity. Second, integrating 3D and 4D printing into the educational system—from technical high schools to university engineering and design programs—would create a skilled workforce capable of driving the next wave of green industrial transformation. Curriculum reform, hands-on laboratories, micro-credential programs, and dual education models would equip young professionals with practical expertise in additive manufacturing, digital twins,

generative design, and smart-material applications. Third, Bosnia and Herzegovina would benefit from a clear regulatory and incentive framework that supports industrial adoption of advanced manufacturing. This could include subsidies for acquiring additive technologies, tax incentives for low-waste production, and competitive grants for green innovation projects in SMEs. Introducing standards for sustainable materials, circular product design, and digital quality assurance would provide firms with modern compliance guidelines while elevating environmental performance across industries. By embedding digital intelligence, material adaptability, and life cycle thinking into its industrial core, the country can transition from being a consumer of imported technologies to a regional leader in smart, circular manufacturing. In this vision, innovation is not abstract—it is tangible, adaptive, and deeply rooted in the landscapes of many cities in Bosnia and Herzegovina where the factories of the future can be built not from steel and smoke, but from data, precision, and regenerative design.

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