Bio-intelligence in Additive Manufacturing

Why we need sustainable manufacturing and regenerative design

Whitepaper 1 of 4, © 2026

organic

Funded by the
European Union

Background of the whitepaper series

The whitepaper series “Bio-intelligence in Additive Manufacturing” is the work of 13 partners who collaborate in the EU-funded ORGANIC project. It is based on one of the first outputs of the project, Deliverable D1.1 to be precise, which serves to facilitate the understanding of the potential of the bio-intelligence concept in additive manufacturing. While all project partners contributed to the content, CARTIF led all actions on the whitepaper.

What to expect

The whitepaper series ‘Bio-intelligence in Additive Manufacturing’ reviews the ongoing scientific, industrial and policy initiatives shaping bio-intelligent manufacturing. It synthesises its current state, identifies enabling technologies and situates the European Horizon Europe ‘Twin Transition’ initiatives within a wider roadmap toward intelligent, circular and adaptive additive manufacturing (AM) systems. The whitepaper series contributes to a broader understanding of how biological, digital and material innovations are converging to define the next generation of manufacturing.

‘Bio-intelligence in Additive Manufacturing’ is brought to you by ORGANIC, an EU-funded project set to boosting the biological transformation of AM processes by integrating bio-design, bio-based materials and bio-intelligent manufacturing into Fused Granulate Fabrication (FGF), a specific AM technology.

The series consists of four separate publications, which detail

- Why we need sustainable manufacturing and regenerative design
- Why conventional additive manufacturing is limited and lacks integration of bio-inspiration and bio-based materials
- How to integrate bio-inspiration and bio-based materials into AM and why it is worth doing so
- Strategies to support industrial adoption of bio-intelligent AM technologies

The first whitepaper sets the scene and explores the context of bio-intelligence in additive manufacturing.

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Disclaimer

ORGANIC is funded by the European Union under the Horizon Europe research and innovation programme, grant agreement No 101178127-1. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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Introduction to bio-intelligent manufacturing

In recent years, the convergence of biological principles, artificial intelligence (AI) and advanced manufacturing has begun to reshape industrial innovation. A new paradigm, commonly referred to as bio-intelligent manufacturing, has emerged from this convergence, introducing a fundamental shift in how materials, processes and systems are conceived, designed and managed.

Integrating four levels

Rather than simply using bio-based materials or biomimetic designs, bio-intelligent manufacturing integrates the adaptive, self-organising and learning capabilities observed in nature into the very logic of industrial production. This integration extends across four levels:

- Bio-inspiration, where the geometrical and structural design of products reflects natural efficiency and multifunctionality
- Bio-based materials, where renewable, circular or recyclable resources replace conventional feedstocks
- Bio-intelligent control, where processes exhibit cognitive properties, monitoring, learning and optimising themselves in real time
- Bio-integrated systems, where manufacturing evolves as a living ecosystem capable of adaptation and regeneration

The bio-intelligent approach transforms the factory into an evolving ecosystem, circular by material, intelligent by design and adaptive by function, paving the way toward a new industrial era that learns and improves as nature does.

Leveraging potential

Within additive manufacturing (AM), commonly known as 3D printing, in which components are built layer by layer directly from digital models, this paradigm finds a particularly fertile ground. AM's intrinsic flexibility and digital nature make it an ideal platform for integrating computer-aided (CA) concepts, from multi-material processing and hierarchical structures to data-driven process evolution.

Pushing the boundaries

Across Europe and internationally, research efforts are expanding the boundaries of this field, linking material science, process engineering, digital twins (DTs) and AI toward a unified vision of sustainable and intelligent production.

Key trends include:

- The increasing use of bio-based and circular polymers, composites, and hybrid materials, supported by advancements in biopolymer chemistry and processability
- The emergence of bio-inspired design tools, integrating generative algorithms, topology optimisation and multi-objective performance models
- The deployment of AI-driven and model-based control architectures capable of real-time optimisation, anomaly detection and self-calibration
- The growing role of DTs and cyber-physical systems, connecting sensing, simulation and decision layers
- The adoption of findable, accessible, interoperable and reusable (FAIR) and open-data principles for knowledge continuity and machine learning across product generations

Why we need sustainable manufacturing and regenerative design

For more than a century, industrial manufacturing has fuelled human progress – driving economic growth, expanding infrastructure and advancing technology. Yet this model, focused on maximising profits and minimising costs, was built on a rapid ‘take-make-dispose’ approach that replaced historic, nature-dependent economies once in balance with natural cycles.

While the shift enabled societies to grow at unprecedented speed, it also normalised patterns of environmental and social harm: overuse of resources, large-scale waste generation, high greenhouse gas emissions, unequal wealth distribution and the erosion of traditional livelihoods, among others.

Overcoming harmful practices

Today, the manufacturing sector faces a pressing need to embrace a new path – one that preserves the social and industrial gains of the past while operating within the earth’s ecological boundaries.

Sustainable manufacturing offers a starting point. It seeks to minimise environmental impact throughout a product’s entire life cycle, from raw material extraction to production, use and end of life.

This can mean using renewable energy, improving resource efficiency, adopting a circular economy, where materials are continually reused, and innovating for sustainability.

Going beyond sustainability

But sustainability alone may not be enough. A more ambitious vision combines sustainable manufacturing with regenerative design principles – strategies that go beyond minimising harm to actively repairing and restoring natural systems.

In this model, manufacturing works like nature: products are designed for stability, functionality and circularity; waste becomes a resource; diversity builds resilience and every stage of a product’s life is planned for a net-positive impact.

This could involve closed-loop material cycles, components that can be easily disassembled and reused, high-performance designs that minimise resource use and production systems optimised for efficiency and minimal waste.

Preserving natural resources

Together, sustainable manufacturing and regenerative design offer a roadmap to an industrial future that can thrive without exhausting the planet’s resources.

Achieving this transformation will require innovation in materials, design methods and technologies – supported by the power of digitalisation to monitor, optimise and connect every step of the process – along with shifts in policy, supply chain management and consumer behaviour (Manikandan et al., 2024)

Striving for innovation

Industrial manufacturing has traditionally relied on four main methods: moulding, machining, joining and forming. While these approaches have proven effective for decades, they are often labour-intensive, slow to adapt to design changes, limited in the complexity of shapes they can produce and responsible for generating significant amounts of material waste.

Exploring a different path

AM takes a fundamentally different path. Instead of removing material to shape a product, AM builds components layer by layer directly from a digital model (Zhou et al., 2024). This approach makes it a natural fit for sustainable manufacturing and regenerative production.

By processing only the material required for each part, AM dramatically reduces waste while enabling lightweight, optimised structures that minimise material use without compromising performance. These efficiencies can also lower energy consumption and greenhouse gas emissions over a product’s life cycle.

Outstanding advantages

AM further shortens production times and reduces prototyping costs by eliminating the need for expensive tooling. Design changes can be made quickly through digital model adjustments, enabling easy customisation without disrupting production. Labour requirements are also reduced, as fewer manual finishing steps are needed. In many cases, AM can produce a complete part in one solid piece, consolidating multiple components into a single, stronger and lighter structure that is simpler to assemble and more efficient to use.

Crucially, AM aligns closely with circular economy principles. It supports the use of bio-based or biodegradable feedstock, enables the repurposing of waste materials into new products and facilitates designs intended for disassembly, repair and reuse – helping to close the loop and move manufacturing toward a truly regenerative model.

Integrating biological inspiration

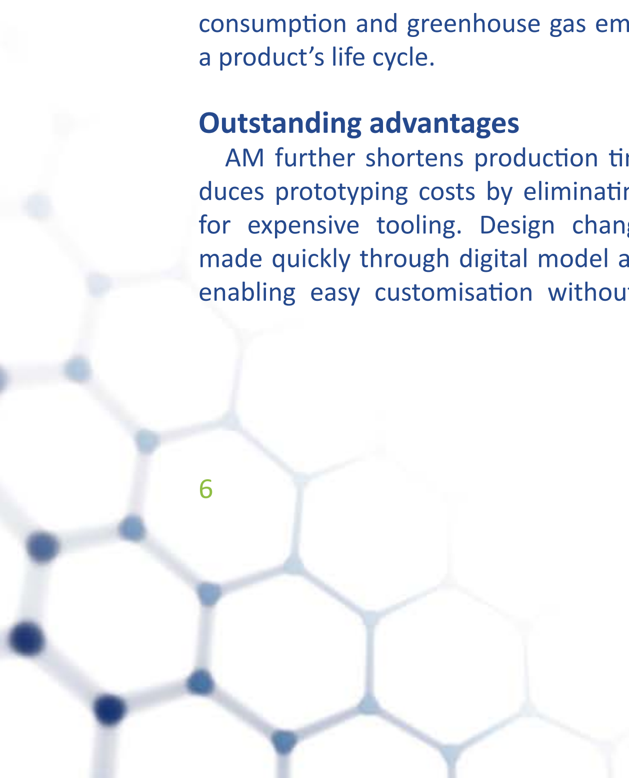
Nowadays, AM is entering a new era in which biological inspiration and advanced digitalisation converge to drive sustainability, efficiency and innovation (Byrne et al., 2021; J. Xu et al., 2024). The demand for more resource-efficient products is reshaping design and production paradigms, pushing industry to move beyond conventional geometries, trial-and-error optimisation and static process control.

Bio-intelligence can be broadly described as the convergence of biological inspiration, computational modelling and AI to create products and processes that mimic, adapt and optimise according to principles found in living organisms.

Building in self-learning capabilities

This concept goes beyond classical biomimetics, which focuses on translating natural forms and mechanisms into engineered solutions by embedding adaptive, data-driven decision-making into the design-manufacturing cycle (Byrne et al., 2021; J. Xu et al., 2024).

Within AM, bio-intelligence can manifest across multiple phases (Emera et al., 2025). During the design phase, designers may use biological systems as analogues for optimised structural efficiency, such as bone trabeculae for lightweight strength, and translate these patterns into manu-



facturable geometries through generative design and topology optimisation (Wei et al., 2023a; H. Zhang et al., 2018).

Implementing AI-driven control systems

For process execution and control, engineers may implement AI-driven control systems inspired by adaptive behaviours in nature, enabling AM processes to self-optimise under varying conditions. In the materials design and selection phase, scientists may draw on biomolecular or hierarchical material structures to inspire the design and application of novel materials with tailored mechanical, thermal or functional properties, while ensuring sustainable sourcing, manufacturing and end-of-life recyclability (Wei et al., 2023a).

This convergence of bio-inspired design, adaptive process control and sustainable materials development signals a paradigm shift for AM. However, the integration of bio-intelligence into AM remains at an early stage, limited by technological maturity, cross-disciplinary integration and industrial adoption.

Aiming for sustainable manufacturing

Building on the growing emphasis on sustainable manufacturing as a balance between economic viability, environmental responsibility and social well-being (Daareyni et al., 2025; Ituarte et al., 2025), emerging AM practices increasingly adopt a bio-intelligent and regenerative perspective.

Achieving sustainability by design

In this context, sustainability-by-design becomes essential: rather than treating environmental aspects as downstream constraints, advanced computer-aided technologies (CAx) environments allow designers to embed indicators such as carbon and water footprint directly in the early stages of product definition.

CAx link design, materials, manufacturing and sustainability considerations, enabling engineers to capture Process-Structure-Property-Performance (PSPP) relationships and explore trade-offs between technical functionality and ecological impact. Such integrated, data-driven workflows provide the basis for bio-inspired and regenerative design methodologies, in which products and processes are conceived to deliver net-positive value over their life cycles.

Exploring large-format AM

Within this framework, AM offers a concrete pathway toward more sustainable production through digital workflows, design flexibility and reduced material waste. However, conventional AM is still limited by build volume, throughput and material options. Large-format additive manufacturing (LFAM), also referred to as large-area AM, addresses many of these constraints by enabling high-throughput fabrication of complex multimaterial structures, often using fibre- or bio-reinforced feedstocks (Daareyni et al., 2025).

Combined with advanced CAx tools, LFAM supports parametric and generative design strategies coupled with sustainability models, helping designers balance structural performance, manufacturability and environmental impact (Daareyni et al., 2025).

Together, these developments prepare the ground for biologically inspired and regenerative AM approaches, where large-format fabrication, sustainable materials and intelligent CAx integration converge to support adaptive, net-positive manufacturing systems.

Looking ahead

The second whitepaper of the series will examine these limitations and challenges in detail, together with state-of-the-art alternatives currently being explored, to frame the approach that the ORGANIC project will take in developing a holistic framework that combines design, manufacturing and the selection, integration and use of advanced bio-based materials.

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R-NANO
University of Applied Sciences and Arts of Southern Switzerland SUPSI
Tampere University

The ORGANIC partners at the start of the project in June 2025.

Imprint

This whitepaper is published on behalf of the ORGANIC consortium by:

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