



Bio-intelligence in Additive Manufacturing

Why conventional additive manufacturing
is limited and lacks integration of
bio-inspiration and bio-based materials

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 second whitepaper explores the limitations of conventional additive manufacturing.

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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



The limitations of conventional additive manufacturing

While additive manufacturing (AM) has advanced significantly in precision, customisation and design freedom, it continues to face persistent limitations that delay its sustainable and scalable adoption. Current processes are often energy- and material-intensive, rely on feedstocks with limited recyclability and operate with static control systems with limited adaptability to evolving production demands.

These constraints increase environmental impact and reduce efficiency as well as the ability to respond to quality or performance deviations in real time. In parallel, the integration of bio-inspired design and bio-based materials – key enablers of lightweight, functional and circular products – remains fragmented.

Translating complex natural architectures into manufacturable AM designs poses technical challenges, while many promising bio-based materials are not yet ready for large-scale deployment. The lack of intelligent, adaptable and circular AM value chains further limits systematic reuse of materials and knowledge across the product lifecycle. Addressing these interconnected gaps is essential to realise a new generation of bio-intelligent, resource-efficient AM processes.

Energy/material inefficiencies, limited recyclability, static control systems

Demonstrating AM durability, safety and cost-effectiveness across a wide range of industries will be essential for building trust and accelerating its adoption. Although equipment costs have decreased compared with the heavy investments required for traditional subtractive manufacturing, the initial capital for industrial-scale extrusion-based AM remains substantial.

Justifying investment

To be widely adopted in real-world production environments, these investments must be justified through consistent performance, quality and cost-effectiveness – benchmarks that still need to be conclusively demonstrated.

Harnessing multiple disciplines

Another adoption barrier lies in the multidisciplinary expertise required for AM integration into traditional manufacturing environments. AM demands knowledge spanning design optimisation, simulation, material science, mechatronics and digital control tools.

This requires skilled operators with specialised training in a field that is continuously evolving. The required steep learning curve makes workforce development a critical challenge.

Although AM generally produces less waste than conventional methods, it is not inherently waste-free. Failed prints, disposable support structures and leftover powder or filament can accumulate. These byproducts are often difficult or costly to recycle. Moreover, certain materials can degrade after multiple reuse cycles, reducing quality and limiting circularity.

Avoiding waste even better

The inclusion of bio-based or biodegradable feedstocks offers potential for greener production, but these materials are still in the initial stages of

development. They remain limited in availability, often have narrower performance windows and require further validation of their environmental benefits.

Similarly, the materials library for AM remains limited compared to traditional manufacturing, although ongoing research is rapidly expanding the range of viable metals, polymers and composites. In particular, fibre-reinforced polymer composites – using short or continuous fibres – are emerging as a key route to achieve high specific stiffness and strength in additively manufactured structures while maintaining lightweight design and geometric complexity (Ramful, 2025).

Limiting environmental impact

Energy consumption also remains a concern, particularly in high-performance applications. Many AM technologies require intense heat or energy sources to preheat, sinter or fuse materials, resulting in high energy demands to match the mechanical performance of traditionally manufactured parts.

Without renewable energy sources or more efficient processing methods, this can diminish AM's environmental advantages.

Improving process control

Process control is another critical challenge. Most conventional AM systems operate with not fully understood processing parameters and limited real-time monitoring. Once a print begins, there is often limited ability to adapt to unexpected variations, increasing the risk of defects or failed builds.

Data from printing processes is typically stored locally rather than shared across systems, hindering collective learning, optimisation and predictive maintenance. Without more dynamic,

interconnected control systems, process improvements tend to be slow and inconsistently applied.

Lacking competitiveness

Finally, production speed and cost remain significant hurdles. Traditional manufacturing methods – backed by decades of refinement – are highly competitive in terms of throughput and efficiency.

As a result, AM is currently best suited for specific applications such as custom designs, highly complex geometries or advanced material processing, rather than large-scale, high-volume production.

In this sense, AM should be viewed as a complementary technology to traditional manufacturing, expanding the toolkit available for advanced

equipment fabrication rather than replacing established methods outright.

Leveraging potential

The emergence of numerous new AM technologies underscores both the field's rapid evolution and its relative immaturity. Overcoming current limitations will require advances in energy efficiency, material science and recycling technologies, alongside the integration of smart, connected control systems and robust digital workflows.

With these improvements, AM can more fully deliver on its promise as a sustainable, high-performance manufacturing solution – and play a vital role in advancing regenerative industrial design.

Gaps in integrating bio-inspiration and bio-based materials

A core ambition of bio-intelligent AM is to establish material and design frameworks that mimic the efficiency and resilience of natural systems, while maintaining industrial relevance and scalability.

Natural systems offer a wide variety of hierarchical architectures, ranging from cellulose helical fibrils to mineral-organic layering of mollusc shells. However, the direct adoption of these structures into AM workflows is not straightforward, as biological principles often arise from structural logics rather than material formulations.

Inspiration from nature

Biological structures demonstrate remarkable strength, toughness and lightweight performance through finely tuned chemical compositions, interfacial gradients and hierarchical organisation, validated by evolution under broad environmental conditions over millions of years.

While the function of natural material systems emerges through a bottom-up process,

by progressively self-assembling simpler components into more complex, multi-level arrangements, AM imposes a design-driven framework in which material behaviour should adapt to predetermined shapes and processing constraints (Veers & others, 2023).

Turning nature upside down

This fundamental inversion calls for the development of new conceptual frameworks, materials and design tools capable of interpreting nature-inspired patterns, organisational logics and hierarchical forms and redefining them within the constraints and possibilities of advanced manufacturing.

Current efforts to mimic natural structures frequently focus on reproducing organic forms, composite and cellular geometries, however with-out being capable of fully replicating the chemical and physical interactions that give these structures their mechanical resilience (Mishnaevsky Jr., 2017; Murdy & Hughes, 2020).

For example, natural composites may combine organic and inorganic phases through finely tuned compositional and spatial gradients, in combination with controlled defect distributions and sacrificial bonds that dissipate energy and promote damage delocalisation (Veers & others, 2023).

Challenging to parametrise

As a result, bio-inspired architectures are difficult to parameterise mathematically. While topology optimisation can provide significant weight savings in generic structures, it does not inherently produce the hierarchical arrangements and gradient transitions characteristic of biological systems (Srivastava & Kawakami, 2023; J. Wu et al., 2021).

In parallel, generative design and CAX-based workflows provide a systematic means of exploring bio-inspired topologies. However, they are typically limited to single-objective problems and face difficulties in simulating heterogeneous material distributions, complex multiscale interactions and integrating manufacturability constraints (Siddiqui et al., 2025; Wang et al., 2020; Wei et al., 2023b; M. S. Wu, 2011; Deaton & Grandhi, 2014; Sigmund & Maute, 2013; Tang et al., 2018).

Lacking the full picture

Even in the case of advanced computational models or generative design tools, the representations typically operate at distinct but disconnected scales, without fully considering material-specific aspects such as rheological behaviour, crystallisation kinetics, localised gradients and interfacial phenomena (Peckham & others, 2024).

In this context, the integration of bio-inspiration into CAX-based workflows is closely related with the ability of materials to function within design-driven processes.

In conventional plastics manufacturing, polymers are routinely formulated and optimised to meet the requirements of specific forming processes. Plastic converters have developed extensive databases of material properties, standards and qualification protocols.

Missing materials library for LFAM

This form of consolidated knowledge is still

missing from the large-format-AM (LFAM) industry (Kawalkar et al., 2022), with early-stage frameworks lacking widespread adoption and integration into material databases.

This gap is particularly critical for emerging bio-based polymers and fibre-reinforced composites, whose processing windows are not yet fully validated.

Weighing up capabilities

Although bio-based materials can provide unique performance capabilities (Wagermaier et al., 2025), their deployment in demanding applications is limited due to inferior mechanical properties, thermal stability and susceptibility to environmental degradation (McKay et al., 2024).

When used in LFAM, these sensitivities translate into tighter processing windows and greater dependence on precise thermal and moisture management.

Varying validation

Technological readiness also varies widely among bio-based polymers, as many products remain only partially validated for processing and smaller production scales increase batch-to-batch and inter-supplier variability (Laycock et al., 2023).

Notable examples of bio-based plastics that have reached a higher technological maturity include bio-based grades of polyethylene terephthalate (PET), polypropylene (PP), polybutylene terephthalate (PBT), polycarbonate (PC) and polyamide (PA), where processing behaviour is well understood and supply chains are established (Bhatia & Sehgal, 2023; Patel & Taufik, 2024).

Many bio-based candidates remain at lower readiness levels, with limited supply, variable quality and incomplete processing data, restricting their use in LFAM (Pignatelli & Percoco, 2022).

Facing constraints

On the manufacturing side, the dynamic thermo-rheological characteristics of feedstock material govern LFAM extrudate shape integrity and coalescence (Owens et al., 2022; Tagscherer et al., 2022). LFAM provides the throughput required for large bio-inspired structures, however

at the cost of reduced resolution (Weerasekera et al., 2022; Wirth & others, 2024), imposing additional constraints in path-planning (Compton et al., 2017).

As build dimensions increase, material's anisotropic shrinkage and compression may cause accumulative effects of delamination, cross-sectional tapering and warpage (Vicente, Sardinha, Reis, & others, 2023).

These phenomena are strongly dependent on the periodic temperature and pressure fluctuation resulting from deposition, cooling and reheating of each layer (Goh et al., 2024). Consequently, to isolate intrinsic material and process effects, structured methodologies and harmonised characterisation protocols are required for material and component qualification (Vicente, Sardinha, Reis, & others, 2023).

Adding complexity

These challenges become more pronounced in the case of AM feedstock materials with higher complexity, such as fibre-reinforced composites, especially when fibre orientation and curved reinforcement paths are critical (Castelló-Pedrero & others, 2024; Ren & others, 2024).

Overcoming mechanical limitations

Fibre reinforcement offers a direct route to overcoming the intrinsic mechanical limitations of neat bio-based thermoplastics and extending their use in structural LFAM applications (Moreno Nieto & Molina, 2020). Chopped fibre composites can significantly enhance stiffness, strength and thermal conductivity (Colón Quintana et al., 2022).

Continuous-fibre reinforcement provides even greater improvements in strength and stiffness, enabling load-bearing capabilities, but imposes strict requirements on fibre impregnation and placement accuracy (Pappas et al., 2021).

Achieving consistent consolidation therefore requires processing windows that stabilise fibre alignment while preserving interlayer bonding and dimensional accuracy.

Developing bio-intelligent AM

While bio-inspiration and bio-based materials provide the conceptual and material foundations

of bio-intelligent AM, their true impact depends on aligning these developments with sustainability principles that ensure circularity, safety and long-term socio-environmental viability (Kravchenko et al., 2020). However, the environmental benefits of bio-based materials are not guaranteed by origin alone.

A comprehensive evaluation framework, involving life-cycle assessment (LCA) and Safe-and-Sustainable-by-Design (SSbD) principles, is needed to balance performance with environmental and socio-economic impacts.

Moving beyond cost and performance

While conventional material selection remains driven primarily by cost and performance metrics, sustainable material selection embeds additional criteria that integrate environmental assessment, carbon footprint, energy demand, chemical safety, end-of-life management, circular-economy strategies, ethical sourcing and stakeholder participation, to establish a balanced and transparent basis for comparative assessment (Su et al., 2024; Chen, 2025).

Material selection emerges as a strategic point instead of a purely technical matter (Sakao et al., 2024). Multi-criteria decision making (MCDM) methods provide structured frameworks to weigh material properties, cost, carbon footprint, recyclability, toxicity and regulatory compliance simultaneously (Agrawal, 2021).

These frameworks are particularly valuable in AM, where bio-based and recycled feedstocks exhibit property variability and incomplete data to allow for direct one-to-one comparisons.

Enhancing trade-off evaluation

Integrating MCDM with LCA, characterisation and processing data enables the explicit evaluation of trade-offs between environmental impact and functional performance. Without such integration, the adoption of bio-based and recycled materials in AM risks remaining superficial, undermining the broader objectives of circular economy and sustainable innovation.

Need for adaptable, intelligent and circular AM value chains

AM increasingly depends on digital platforms to connect design, production and quality control. However, most platforms remain fragmented and isolated across the value chain, limiting data exchange and adaptive process control. While Industry 4.0 standards have enabled partial automation, AM platforms still lack the mechanisms to evolve and learn from cumulative production knowledge – an essential capability for achieving self-improving, circular and bio-intelligent manufacturing systems.

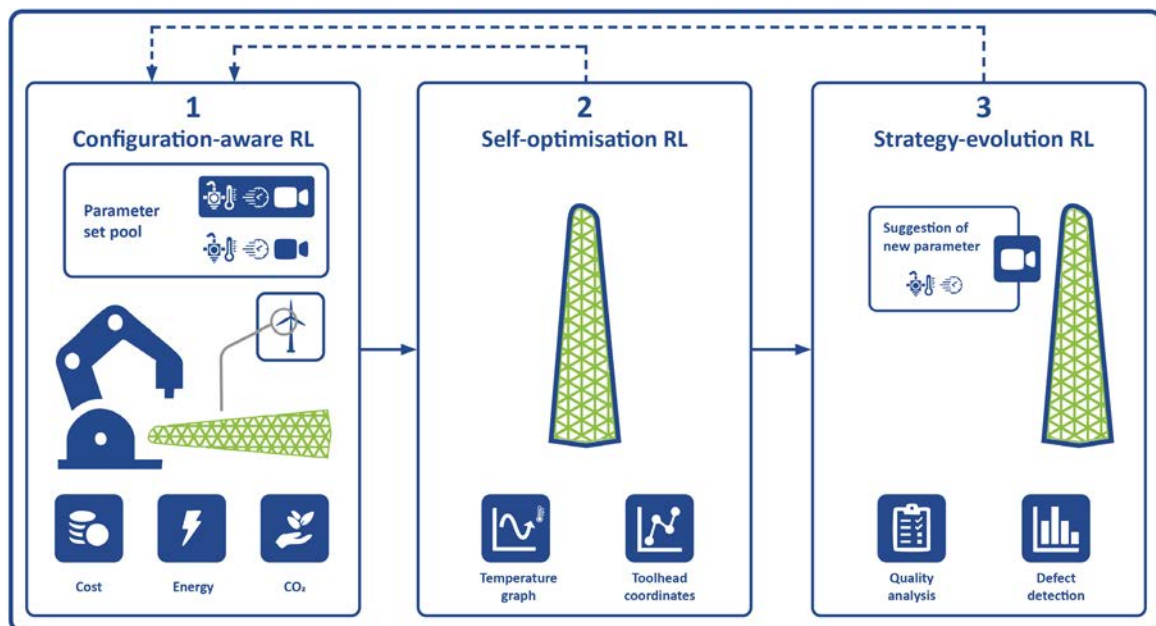


Figure 1: Reinforcement Learning (RL) workflow for ORGAMIC, illustrating self-optimisation R, and strategy-evolution RL for adaptive AM process improvement

Integration barriers and lack of interoperability

Despite advances in digitalisation, contemporary manufacturing platforms face substantial integration challenges that limit their ability to support bio-intelligent AM workflows. Design tools, process monitoring systems and quality databases typically operate as fragmented systems with limited interoperability, preventing seamless data flow from design optimisation through fabrication to process intelligence.

Absence of standardised asset representations

Manufacturing equipment, sensors and materials lack standardised asset representations such as Asset Administration Shells (AAS), which restricts real-time visibility into asset capabilities and restrains dynamic reconfiguration in response to changing production demands (IDTA – Working Together to Promote the Digital Twin, 2023).

This absence of a unified, internationally accepted standardisation framework forces current DT implementations to rely heavily on application specific or vendor tailored data models which limits system interoperability (David et al., 2025).

Specifically, the problems emerge as:

- **Heterogeneous data structures**
Industrial assets, control systems and enterprise resource tools utilise varied, non-uniform data schemas. This data isolation prevents seamless, automated interpretation of asset state, history and capabilities across different platforms and lifecycle phases.
- **Restricted semantic interoperability**
Without standardised metadata and contextual descriptions, systems face challenges automatically interpreting the meaning (semantics) of the exchanged data.

- **Barrier to scalability**

The deployment of AI-driven and model-based control architectures capable of real-time optimisation, anomaly detection and self-calibration.

Limitations of existing initiatives

Although previous European initiatives such as DIMOFAC have demonstrated strong foundations for modular, plug-and-produce manufacturing and lifecycle management, these frameworks still fall short in offering closed-loop intelligence as they lack the infrastructure to integrate real-time sensor data with adaptive learning algorithms, preventing the closed-loop intelligence required for self-optimising manufacturing systems (Digital Intelligent MODular FACTories | DIMOFAC | European Commission, 2023).

Unresolved cloud-edge integration

The disconnect between edge computing requirements for real-time control and cloud computing benefits for scalable training and analytics remains largely unresolved, as current platforms offer poor cloud-edge integration, namely they do not provide hybrid architectures with secure connectivity and automated model deployment across distributed layers (Eclipse BaSyx™, 2024).

The need for continuous learning

As industries transition toward more sustainable and circular production models, AM must evolve from static, parameter-bound systems to intelligent, adaptive frameworks capable of continuous learning.

Current AM approaches lack the ability to interpret and act upon cross-process knowledge over time, limiting their capacity to optimise resource use, integrate new materials and respond to changing design and sustainability requirements (Kellens, Renaldi, et al., 2017).

Underutilised data potential in digitalised AM systems

At the same time, despite the increasing digitalisation of AM and the deployment of sensors and DTs, most systems still struggle to capture, structure and exploit the large volumes of data they generate.

The potential to extract meaningful knowledge from geometry, material properties and process conditions therefore remains largely underutilised, constraining the development of adaptive, knowledge-driven design and optimisation strategies.

Knowledge graphs and ontological models as enablers

To move from data-rich yet static processes toward truly self-improving and evolutionary manufacturing, AM systems need structured knowledge representations that enable reasoning over this information.

Knowledge graph frameworks and ontological models offer a way to formalise relationships and merge existing expert or theoretical knowledge about AM (what is already known) with new knowledge extracted from real-world data and experiments into a coherent, interconnected framework.

The remaining challenge is to endow these representations with the ability to derive predictive insights on manufacturability and to generate AM design rules autonomously. Addressing this gap is essential for transforming AM into an intelligent, continuously learning process that can be effectively leveraged by AI-based solutions.

Limitations of current optimisation strategies

While a variety of adaptive and learning-based optimisation strategies, such as multi-criteria optimisation, evolutionary algorithms and genetic approaches, have demonstrated potential for balancing complex trade-offs in AM, e.g., cost, quality and environmental impact (Jin et al., 2020; Stief et al., 2019; W. Yang et al., 2020; M. Zhang

et al., 2021), their adaptability over long temporal and contextual horizons remains limited.

Reinforcement learning as a promising framework

Reinforcement Learning (RL), in contrast, offers a promising framework for cumulative, experience-driven optimisation, enabling systems to refine decision-making policies through interaction and feedback. Recent studies have explored RL in broader manufacturing contexts, demonstrating its potential for autonomous process control (Nievas et al., 2024) and deep RL-based production system optimisation (Panzer & Bender, 2022). However, current applications of RL in AM remain narrow, often confined to short-term process tuning and isolated control loops (Modrak et al., 2024).

Extending RL to the systems level

A critical gap therefore persists in extending RL to the systems level, where manufacturing knowledge spanning the entire product lifecycle can be structured, learned from and reused to guide long-term, adaptive evolution of AM processes (Tao et al., 2018).

Addressing this gap is vital to realising AM value chains that are not only circular and resource-efficient, but also self-improving, capable of adapting continuously to new use cases, materials and environmental constraints through cumulative, life-long learning (Monostori et al., 2016).

Looking ahead...

The now following whitepaper introduces the proposal ORGANIC will give – a next-generation framework for intelligent, bio-inspired AM that directly addresses the integration, adaptability and knowledge gaps identified in current AM systems.

The ORGANIC concept

Drawing on principles from biological self-organisation, the ORGANIC concept proposes a unified architecture in which design, fabrication and process control evolve continuously through cumulative learning.

Bio-inspired design and sustainable materials

The framework encompasses bio-inspired design methodologies and sustainable material strategies that align structural performance with circular economy principles, enabling AM systems to respond dynamically to evolving functional and environmental requirements.

Smart process control with self-X and AI

Smart process control mechanisms underpinned by self-X capabilities – including self-optimisation, self-healing and self-configuration – are powered by reinforcement learning and AI, allowing the system to refine its behaviour autonomously through operational experience.

Digital platform and knowledge models

A coherent digital platform ties these elements together through standardised knowledge models, ontological representations and interoperable asset descriptions, enabling seamless data flow and shared intelligence across the full manufacturing lifecycle.

AM fabrication systems

The whitepaper further details the AM fabrication systems through which the ORGANIC concept is demonstrated, spanning hardware integration, sensor fusion and closed-loop process intelligence.

Demonstration and integration

A dedicated demonstration and integration chapter presents real-world validation scenarios that illustrate how the proposed architecture performs under operational conditions.

Benefits and impact

Finally, the expected benefits and broader impact are assessed, highlighting gains in resource efficiency, production adaptability and manufacturing intelligence.

Collectively, the ORGANIC framework represents a concrete pathway toward self-improving, bio-intelligent AM value chains capable of continuous evolution in response to changing materials, design requirements and sustainability targets.

ORGANIC partners



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

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