BE-AM

BUILT ENVIRONMENT

ADDITIVE MANUFACTURING

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BE-AM 2025 SYMPOSIUM

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INTRODUCTION

PREFACE

10 Years of BE-AM

With the 2025 edition, BE-AM celebrates its tenth anniversary. What began as a small gathering at TU Darmstadt has evolved into an established international platform for additive manufacturing in architecture. Since joining Formnext – the world's leading trade fair for additive manufacturing – for the seventh time, BE-AM has continuously expanded its reach and impact.

Over the past decade, BE-AM has become more than an annual event: it has grown into a network, a community, and a recognizable brand. Through symposia, exhibitions, research collaborations, discussions, live streams, publications, and digital archives, BE-AM has fostered an ongoing exchange between academia and industry. More than 70 presentations have attracted close to a thousand participants, and countless prototypes have been exhibited – often distinguished by their unusual scale and experimental ambition. We are deeply grateful to all contributors, speakers, exhibitors, and supporters who have shaped this journey.

As the field of additive manufacturing for the built environment has matured, so has BE-AM. Having established a strong foundation in research and dissemination, it is now time to focus on technology transfer and market implementation. Accordingly, the 2025 edition emphasizes industrial applications and showcases pioneering work from practice. Additively manufactured components have reached a level of scale and robustness that makes them increasingly relevant for construction – a transformation we are excited to accompany and accelerate.

We look forward to the next decade of exploration, collaboration, and progress – and to welcoming you once again as part of BE-AM.

Oliver Tessmann,
Ulrich Knaack,
Alexander Wolf

ESSAYS

Fig. 1: White Tower’s 3D-printed columns, Photo: Che Wei Lin

BRIDGING CUSTOM AND SERIAL: INTEGRATED 3D CONCRETE PRINTING

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Abstract

The construction industry faces a fundamental challenge: how to efficiently produce both unique architectural elements and a small series of repetitive components while maintaining high quality and controlling costs. This research presents a hybrid digital fabrication approach that strategically combines direct 3D concrete printing with cast concrete using 3D-printed polymer formwork. Developed by Ana Anton and Benjamin Dillenburger at ETH Zurich, in collaboration with Matthias Leschok (SAEKI) and Ammar Mirjan (MESH), this methodology addresses the specific needs of prefabricated concrete construction, where components are often one-of-a-kind or repeated only in small batches within individual projects.

The key innovation lies in recognizing that different architectural elements demand different fabrication strategies. By pairing robotic concrete extrusion for unique components with reusable polymer formwork for repetitive elements, the approach optimizes material efficiency, structural performance, and production economics. Column elements, for example, utilize 3D-printed concrete for main shafts where geometric variation is highest, while bases and capitals are cast in polymer formwork where connection details and embedded infrastructure demand the precision and material isotropy of cast concrete. This strategic pairing enables production workflows where direct printing consumes no setup time and adapts instantly to geometric changes, while reusable molds accommodate intricate reinforcement arrangements and electrical conduits. This hybrid system demonstrates particular promise for design-for-disassembly applications and represents a significant step toward the full digitalization of concrete construction workflows.

The Challenge of Contemporary Prefabrication

Modern architectural practice increasingly demands geometric complexity and customization, yet the economics of construction favor standardization and repetition. Prefabricated concrete construction operates in this tension zone, where projects typically require a mix of bespoke elements and components repeated multiple times. Traditional methods struggle with this scenario: custom formwork for unique parts becomes prohibitively expensive, while maintaining precision across small production runs remains labor-intensive.

Furthermore, the construction industry faces mounting pressure to reduce material consumption, automate labor-intensive processes, and develop assembly systems that facilitate future reuse and disassembly. Conventional concrete construction, despite its structural advantages, often results in substantial material waste and components that are difficult to separate or recycle at end-of-life. These challenges call for fabrication strategies that can accommodate geometric freedom while maintaining economic viability at small scales.

A Dual-Strategy Approach

The research proposes a strategic division of fabrication methods based on component characteristics. For one-of-a-kind elements, such as the main shafts of columns with varying geometries, direct 3D concrete printing offers compelling advantages. The technology enables rapid production without tooling costs, accommodates complex geometries, and allows for the integration of reinforcement during the printing process. Large hollow volumes can be created efficiently, reducing material consumption while maintaining structural capacity. The high degree of automation minimizes labor requirements and improves consistency.

For components that repeat within a project, particularly those requiring isotropic material behavior or complex embedded connections, the research employs cast concrete using 3D-printed polymer formwork. This method combines the geometric freedom of additive manufacturing with the material properties and surface quality of conventional casting. Unlike direct printing, cast components can achieve fully isotropic strength characteristics and accommodate dense reinforcement arrangements. The reusability of polymer formwork makes this approach economically competitive for production runs as small as four to eight units, a scale where traditional formwork fabrication becomes cost-prohibitive.

Polymer Formwork: Design and Production

The development of polymer 3D-printed formwork represented a critical innovation within the overall system. Large-scale polymer extrusion using engineering thermoplastics created robust, reusable molds capable of withstanding the rigors of industrial precasting. For medium and large components, ABS reinforced with 20 percent glass fiber content provided exceptional stiffness, dimensional stability, and machinability. Smaller or less mechanically demanding parts utilized fiber-reinforced polypropylene, reducing both weight and material costs while maintaining adequate performance.

Both materials demonstrated resistance to the alkalinity of fresh concrete, enabling direct casting without surface coatings or liners. Only a thin layer of release agent was required before each use. This chemical compatibility, combined with mechanical robustness, distinguished polymer formwork from alternative approaches such as sand-based 3D-printed molds, which rely on epoxy-resin coatings to achieve high concrete surface quality and typically fail after a single use, proving vulnerable to hydrostatic pressure and vibration during casting.

The fabrication workflow integrated additive and subtractive processes. Following 3D printing with optimized parameters, including a layer height of 3.5 millimeters, a layer width of 12 millimeters, and two outline passes, each formwork segment underwent CNC machining. This subtractive step achieved the fair-faced concrete surface quality and dimensional accuracy required for final assembly, with tolerances of ±0.5 millimeters maintained across surfaces exceeding two meters in length.

The machining process served multiple functions beyond surface refinement. Shallow engravings two millimeters deep were introduced directly into the formwork interior, indicating the precise outlines of adjoining components and embedded elements. These guides minimized manual labor during pre-assembly, allowing workers to position connection hardware, reinforcement elements, and electrical infrastructure with confidence. Additionally, the contours of adjacent 3D-printed concrete columns were engraved into corresponding base and capital molds, creating visual registration marks for applying the glue between the cast and 3D-printed concrete that ensured accurate alignment during assembly.

Performance and Economic Advantages

The mechanical performance of polymer formwork proved superior to alternatives throughout casting and handling operations. The molds remained unaffected by hydrostatic pressure from fluid concrete, accommodated complex reinforcement placement without damage, withstood vibration during concrete consolidation, and survived demolding operations without deformation.

Fig. 2: Casting

Most significantly, they could be reused multiple times without degradation. For the Tor Alva demonstration project, this robustness meant that only one set of polymer formworks was fabricated for each column typology, yielding substantial savings in production time and cost compared to single-use approaches.

This reusability fundamentally altered the economics of small-series prefabrication. While traditional custom formwork might require prohibitive investment for production runs under ten units, and sand-based 3D-printed formwork demands a new print for each casting, polymer formwork achieves cost-effectiveness at repetition counts as low as four to eight units. This range aligns precisely with the typical requirements of contemporary architectural projects, where identical components recur within individual floors or building sections but rarely extend across entire structures.

Beyond immediate production efficiency, the polymer formwork approach supports material circularity. Both ABS with glass fiber reinforcement and fiber-reinforced polypropylene can be shredded and repelletized after their service life, closing the material loop and minimizing waste. This recyclability extends the environmental benefits beyond the initial use phase, contributing to broader sustainability goals in construction.

Rebar Reinforced 3D Concrete Printing

The complementary direct 3D concrete printing process addressed components requiring unique geometries. This part of the project was a major interdisciplinary research achievement addressed within an Innosuisse project by the chairs of Digital Building Technologies, Concrete Structures and Bridge Design, and Physical Chemistry of Building Materials from ETH Zurich, in collaboration with Zindel and MESH as industry partners. Robotic extrusion of reinforced concrete enabled the fabrication of over fifty-one-of-a-kind columns, each tailored to specific structural [2,3] and architectural [1] requirements. A critical advancement in this process was the automated integration of reinforcement during printing, which fundamentally distinguishes this approach from unreinforced 3D-printed concrete applications.

The reinforcement integration system operated synchronously with the concrete extrusion process. As the robotic arm deposited material layer by layer, horizontal reinforcement bars were positioned and embedded directly into the fresh concrete, every 200 mm or 25th layer. This in-process integration enabled branching column typologies impossible to produce with post-printing reinforcement installation and ensured

Fig. 3: Storey plates

Fig. 4: 3D-Concrete extrusion @ ETHZ RFL, Photo: Girts Apskalns

optimal bond between steel and concrete matrix. The timing proved critical: circular shear reinforcement bars were placed into layers at the precise moment when the concrete had sufficient initial yield strength to support the steel while remaining plastic enough to achieve full encapsulation and bond development.

This automated reinforcement placement transformed 3D-printed concrete from a primarily architectural medium into a structurally viable construction method. The horizontal rebar provided tensile capacity essential for load-bearing applications, while the printing process itself created the compressive concrete matrix. The integration of both materials within a single continuous fabrication workflow represented a significant technical achievement, requiring coordination between robotic motion planning, material deposition rates, concrete rheology, and reinforcement handling systems. For the Tor Alva columns, this capability enabled the creation of structurally competent vertical elements that met engineering requirements while maintaining the geometric freedom inherent to additive manufacturing.

The Tor Alva Demonstration

The Tor Alva project provided a comprehensive demonstration of the hybrid fabrication approach and structured information exchange with industry partners to enable lean fabrication strategies. The design requirements demanded an interplay between structural performance, geometric complexity, and architectural expression that conventional fabrication methods would have struggled to address economically. Each tower level followed a shared generative logic with subtle geometric variations, creating exactly the production scenario where hybrid fabrication offers maximum advantage: a combination of unique elements and small-series repetition. The design-to-fabrication team of Tor Alva provided different types of documentation for each fabrication step. The 3D-printed formwork used 3D models for the overall shape and 3D curves for the shallow engravings. Construction drawings were shared with the precast company for the overall shape and assembly of the functional elements before casting. For the interlayer rebar, a list with the number of pieces of each type of diameter was sufficient.

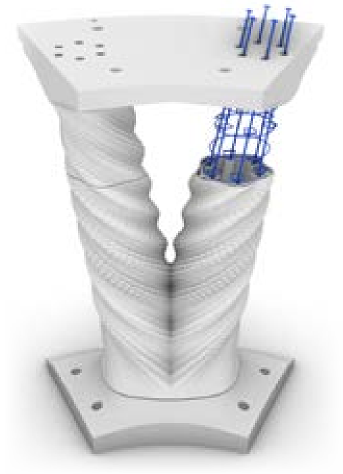

Fig. 5: Model reinforced columns

Fig. 6: Columns Preassembly

The architectural resolution of Tor Alva required fair-faced concrete quality throughout, precision interfaces for assembly and future disassembly, and the integration of complex connection details and electrical infrastructure. The hybrid approach delivered on all requirements. Cast components achieved the surface quality and dimensional accuracy needed for exposed architectural concrete, while 3D-printed elements provided the geometric freedom necessary for the varied column profiles. The engraved registration marks in the formwork facilitated accurate positioning during pre-assembly, ensuring that printed and cast components aligned properly despite their different fabrication origins. The design-for-disassembly strategy benefited from the precision interfaces created through both fabrication methods, facilitating future adaptation or deconstruction.

Conclusions and Future Directions

What this research demonstrates is that concrete fabrication doesn't need to be either/or. By recognizing that different components demand different strategies, we can achieve results that neither method handles well independently. Direct 3D printing works best for unique geometries and hollow, material-efficient sections. Casting in reusable polymer formwork makes sense for components repeated four to eight times, especially when you need complex embedded connections, isotropic material behavior, or fair-faced quality. When you combine these methods strategically within a single assembly, several advantages emerge. Material efficiency improves through hollow printed volumes and reusable formwork. Automation reduces labor, and the engraved positioning guides in the formwork minimize manual layout work. Digital control throughout both processes increases precision. Most importantly, this proves economically viable at the small scales typical of real architectural projects, not just theoretical mass production scenarios.

We're now focusing on connection detail refinement, expanding what building systems this can address, and investigating its role in circular construction. Both the polymer formwork and the approach to concrete elements support recyclability and disassembly, suggesting pathways toward more sustainable building practices. As construction gradually digitalizes, the ability to efficiently handle both one-off and small-series production while maintaining quality and cost control will matter more and more.

Fig. 7: White Tower assembly, Autumn 2024, Photo: Hansmeyer/Dillenburger

Fig. 8: White Tower unveiled, May 20th, Photo: Njat Mahamaliyev

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Fig. 1: 1:10 scale facade prototype composed of 3 × 3 panels fabricated with our flexible mold

A FLEXIBLE MOLD FOR CUSTOMIZED 3D PRINTED FACADE PANELS

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Abstract

The production of non-standard architectural panels is prone to material and cost inefficiencies, as it typically relies on single-use molds that are CNC milled from solid blocks of material. This essay presents a novel computational fabrication solution for the production of customizable free-form panels, achieving high accuracy with minimal waste. Our system relies on an efficient simulation-based optimization model and a flexible membrane that reconfigures its shape through controlled deflation and simple boundary adjustments, accommodating a wide range of single- and double-curvature target geometries. Even if the mold can support numerous fabrication methods, we demonstrate its accuracy by robotically 3D printing and manually casting a set of gypsum panels, as well as presenting a complex facade model featuring significant variations in Gaussian curvature.

Introduction

The striking freeform facades showcased by contemporary architectural projects, such as Foster's Sage Gateshead Music Center, or Snøhetta's King Abdulaziz Center for World Culture, are notoriously challenging to materialize. Specifically, cladding such complex building envelopes requires large fabrication efforts to manage a high number of differently shaped panels using molds. Customized panel molds typically require CNC machining, and often one individual mold is needed per panel type. Efficient fabrication alternatives exist only in special cases, such as hot-wire cut styrofoam molds for developable fiber-reinforced concrete panels. However, most double-curvature shapes still require CNC machining, which is an expensive and environmentally problematic process. One approach to reduce mold quantity is to use a single machined mold for multiple panels through clever design solutions, such as clustering and shape optimization techniques [7]. Alternatively, flexible molds can offer significant advantages over static ones. They adapt to various panel shapes and sizes, especially for complex geometries, while reducing manufacturing time and resource consumption. Current flexible molds use either dense grids of actuated pins or coarser pin grids covered by elastic material for smoother finishes [1,2]. However, these require numerous supporting elements and complex mechanics, with surface resolution depending on pin count. We propose a novel, flexible mold design based on a simpler principle: rather than supporting an entire surface with numerous elements, we demonstrate that supporting only a carefully chosen boundary curve is sufficient. Our approach relies on computational fabrication, requiring an efficient algorithm to solve an inverse design problem. The flexible mold principle can, in principle, adapt to various fabrication methods, ranging from casting to forming to 3D printing, and consequently to multiple different material systems, such as concrete, glass, or bio-based compounds. We here demonstrate the fabrication possibilities of the system by focusing on robotic 3D printing of gypsum [3,9]. Specifically, we demonstrate how conventional layer-based extrusion processes can produce a smooth surface finish – a sought-after feature of facade panels that is not always achievable with large-scale 3D printing methods without additional post-processing steps [4].

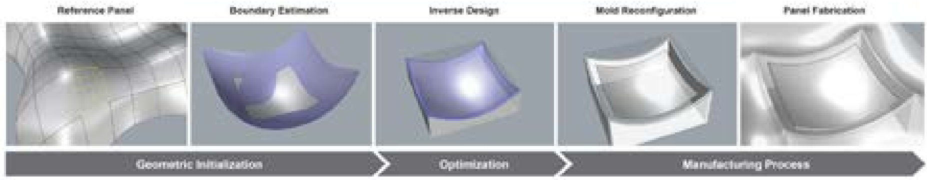


Fig. 2: High-level overview (flowchart from left to right) of the different steps within the presented computational approach.

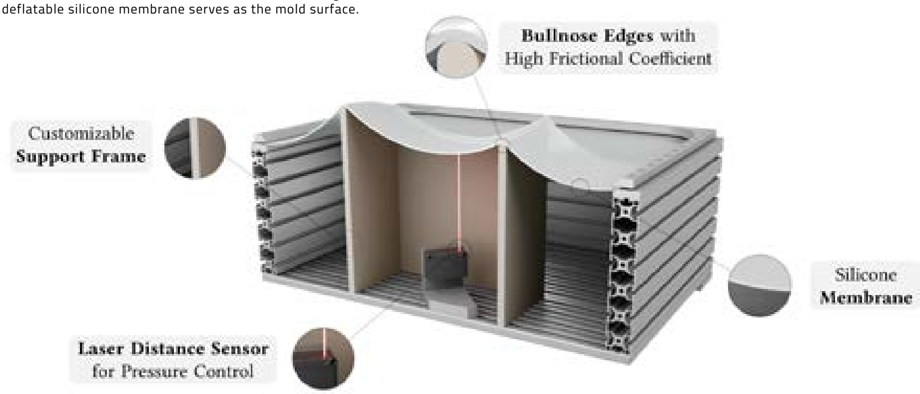
Flexible Mold System

We consider the flexible mold as a system comprising two complementary components: a physically and numerically controlled machine activated by negative air pressure, and a digital simulation and optimization workflow calibrated to the machine's physical characteristics. This design has been initially presented [8] to the visual computing community, which frequently engages with challenging and innovative inverse design problems [5,6]. Such a computational fabrication setup receives a digital target surface as input and produces a set of boundary curves and one air pressure value as outputs. These boundary curves are materialized as a cost-effective and easily fabricable support frame that deforms the physical machine membrane to the desired target geometry when the correct air pressure is applied. We provide a detailed description of the specifications for the two system components.

Computational Design

We developed an efficient computational workflow that integrates seamlessly with our flexible mold machine, optimizing the placement and shape of the customized boundary element to ensure the fabricated panel accurately matches the geometry of a given input shape. As shown in Figure 2, the algorithm starts by inputting a target freeform design surface, from which a reference panel is extracted and approximated by a quadratic Weingarten surface. This family of surfaces is characterized by a specific relation between their principal curvatures, which we use to approximate the stress-strain behavior of the physical membrane. The edges of the Weingarten surface are then extracted to estimate the support curves, which we use as the initial conditions for an inverse simulation loop that optimizes their shape. The digital mold is then reconfigured according to this optimized set of support curves, and the membrane is finally deflated in its ultimate mold configuration.

Fig. 3: The cross-sectional view of the Flexible Mold machine shows the arrangement of the support under the membrane in the area that acts as the mold. The outer aluminum case ensures air tightness, while the deflatable silicone membrane serves as the mold surface.



Machine Design

The machine consists of a membrane and an aluminum alloy box case of the same size, where the membrane is mounted on top of the box before each fabrication session (see Figure 3). The mold surface consists of a 3 mm thick silicone membrane with a Shore A hardness of 40 and a density of 1190 kg/m^3. This membrane is clamped in a two-part machined aluminum frame with inner dimensions of 660 mm × 880 mm × 3 mm (width × depth × thickness). The frame rests on an almost airtight box built from aluminum profiles, with dowel pins ensuring precise positioning. Inside this box, we place CNC-machined MDF board support frames.

When the air pressure inside the box decreases, the membrane deflates and makes contact with the MDF frame. The slightly rough surface at the rounded edge of the MDF board prevents the membrane from slipping during deflation. Two pneumatic Venturi vacuum generators lower the air pressure inside the box below ambient levels. One generator runs continuously (providing a base airflow), while a fast-acting magnetic valve on the high-pressure side controls the second generator. We implement a closed-loop control system by measuring deflation with a laser triangulation distance sensor (Micro-Epsilon ILD1420-200). The support frames are made from CNC-machined MDF boards, with the critical top edge shaped using a 5 mm radius sunk bead cutter.

Fabrication of Freeform Panels

In this section, we demonstrate the capabilities of our flexible mold for efficiently fabricating doubly curved, customized facade panels in various curvature configurations. We produced fabricated panels with Gaussian curvatures $K>0$, $K>>0$, $K<0$ / $K>0$, and $K<0$ (Figure 4, from left to right). The flexible mold is designed to adapt to both traditional and digital production methods and host a variety of material systems, such as the thermoforming of thermoplastic material like PMMA (acrylic glass) or PC (polycarbonate), cast materials like concrete and ceramics, and fiber/resin systems like laminates from glass fiber mates and epoxy resin. Especially interesting is the combination with additive manufacturing technologies. Robotic 3D printing on a flexible mold can produce an accurate outer panel surface finish with precise boundaries, enabling fine control and customization of panel thickness, surface finish, edge geometry, and the integration of additional mounting features. With a multi-axis extrusion 3D printing process, we fabricate sturdy, double-curvature gypsum panels with a monolithic inner volume and a perfectly smooth outer surface. Smoothness of the outer surface is often a required aesthetic feature which, with other 3D printing methods, would require additional post-processing steps and related higher costs. For lower degrees of customization, 3D printing can still provide an efficient integration with the flexible mold in producing customized panel edge profiles required for manual casting processes.

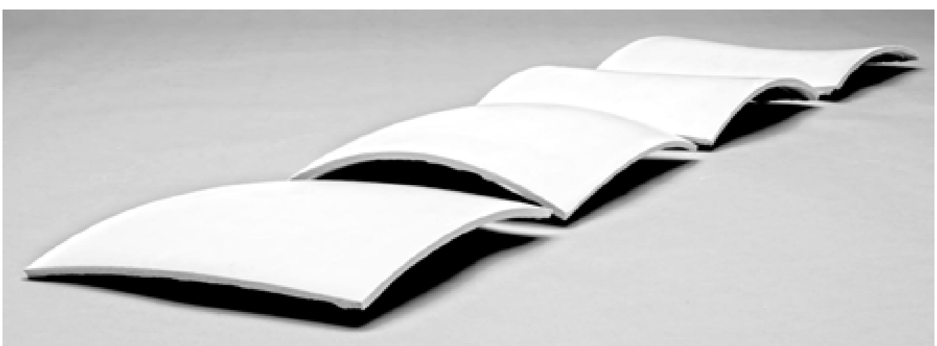


Fig. 4: From left to right, manually fabricated gypsum panels TP1 ($K > 0$), TP2 ($K >> 0$), TP4 ($K < 0$ and $K > 0$), and TP3 ($K < 0$).

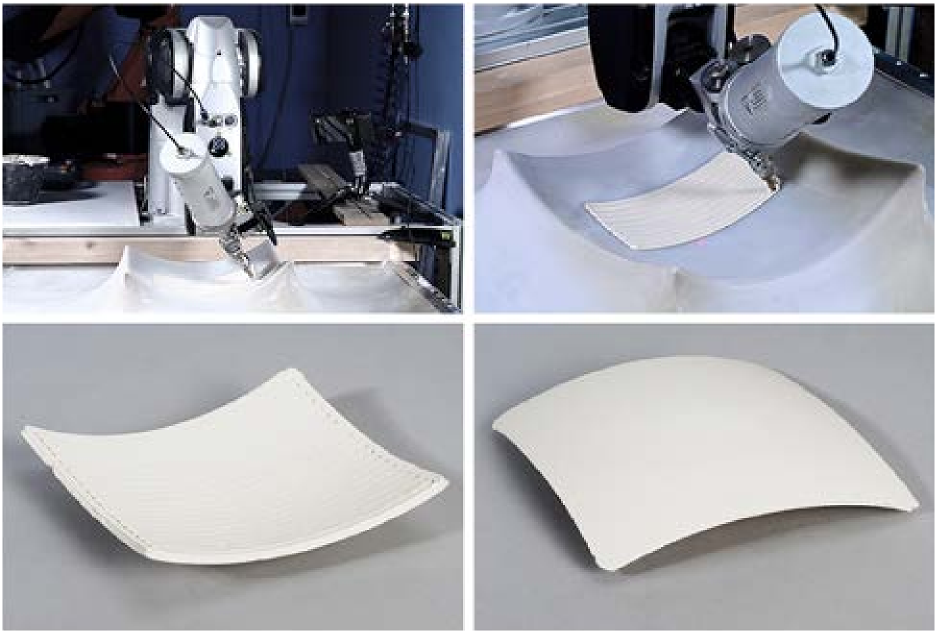


Fig. 5: Panel fabrication via manual gypsum casting. Positioning the flexible foam boundaries on the membrane (top left); material distribution of plaster paste within the panel boundaries (top right); finished panel smooth outer surface (bottom left), and textured inner surface (bottom right).

Fig. 6: Panel fabrication via robotic gypsum 3D printing. Fabrication setup with 6DOF robot arm equipped for extrusion 3D printing (top left); toolpath detail during the first layer deposition, with visible laser distance sensor (top right); finished panel with smooth outer surface (bottom left) and textured inner surface (bottom right).

Manual Casting

Once the membrane is deflated to the desired target pressure, manually producing a panel can be an extremely efficient and intuitive process. Any form of flexible boundary can, in principle, be used to contain the fluid material. As visible in Figure 5, in our experiments, we utilized strips of low-density foam with a 5mm thickness to produce ultra-hard calcium alpha-hydrate gypsum panels. After registering the foam boundary and ensuring sufficient adhesion to the membrane, we poured and spread the viscous plaster evenly on the surface using a spatula. 15 minutes after casting, the hydration process is complete and the panel is ready to be demolded. As visible, panels showcase a perfectly smooth outer surface finish and clean edges.

Robotic 3D Printing

To achieve maximum accuracy and structural integrity in the resulting panels, 3D printing on the freeform surfaces defined by the Flexible Mold requires a fabrication setup that can consistently extrude material along the surface normals of the membrane geometry. We therefore equipped a 6DOF industrial robotic arm (Comau Racer-3-0.63) with a numerically controlled paste extruder (Lutum v10) to deposit a plaster-based joint compound, which has approximately 45 minutes of workability time. Using a custom scripting interface, we can easily program a robot toolpath with synchronized extruder instructions by simply providing a NURBS representation of the panel. We produced a positive Gaussian curvature panel with dimensions of 200 × 200 × 4.5 mm in approximately 20 minutes by programming a 3-layer single-line toolpath, using a nozzle velocity of 0.025 m/s and a layer height of 1.5 mm. In Figure 6, we can see a detail of the first layer deposition, programmed to be slightly over-extruded to ensure a smooth exterior surface finish.

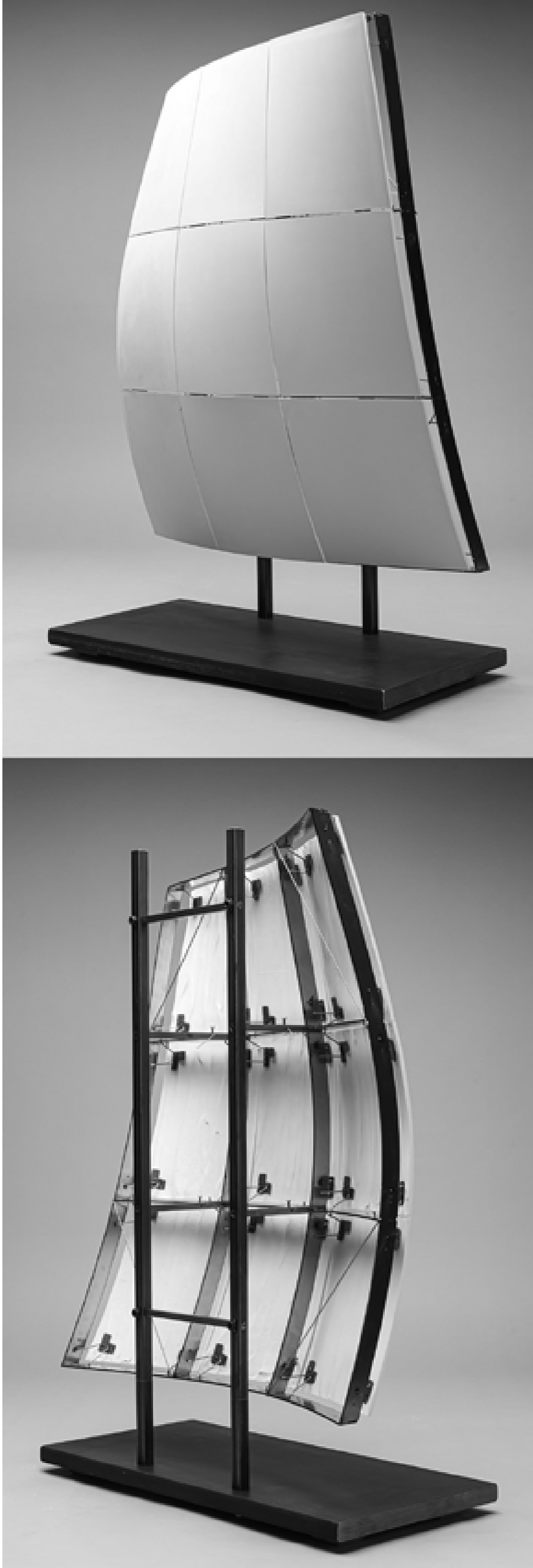


Fig. 7: Photos of the 1:10 scale facade prototype composed of 3 × 3 panels fabricated with our flexible mold. finished panel with smooth outer surface (bottom left) and textured inner surface (bottom right).

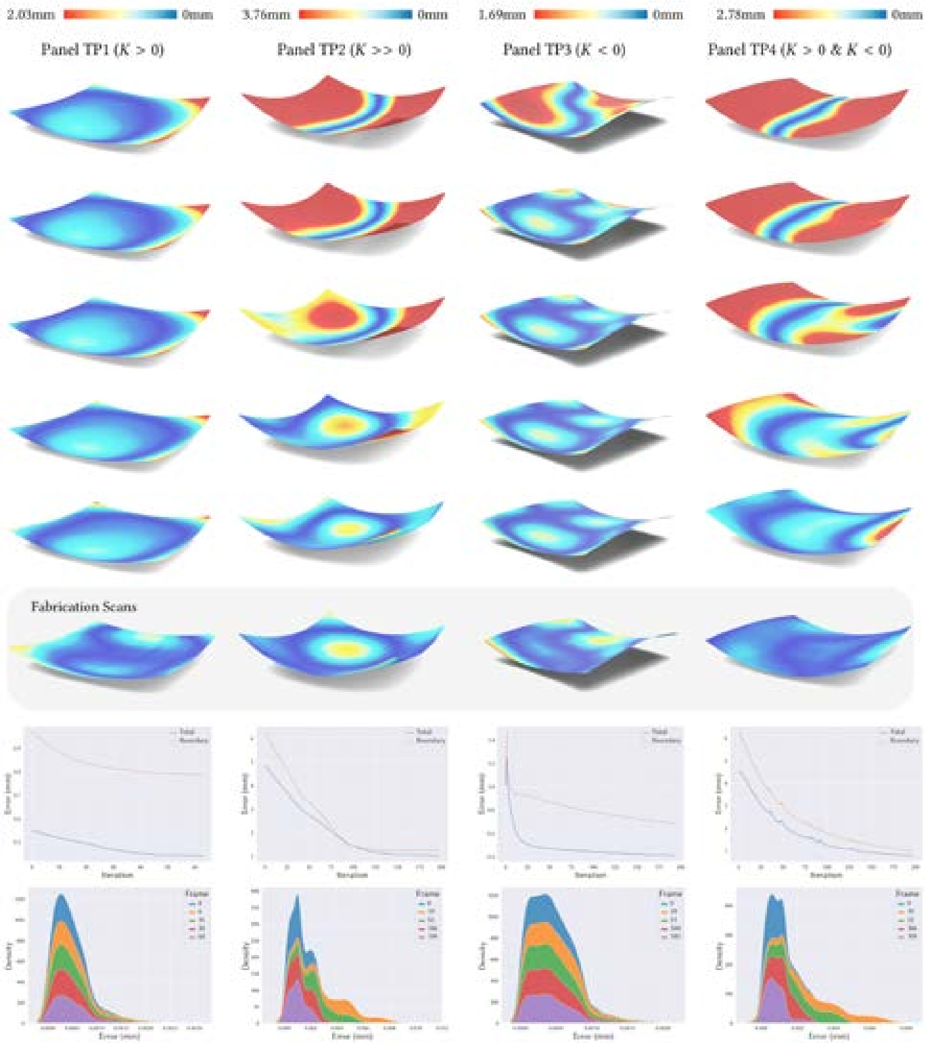


Fig. 8: Results on the four test panels TP1-TP4 (columns 1-4). Colormap encodes distance to the target panel from: Forward simulation with geometric initialization (row 1); simulation-based optimization at various simulation steps (rows 2-5); laser scans of the mold surface (row 6); error curves across simulation iterations (row 7); stacked plots of distance distribution from target panel (row 8).

Accuracy

We selected four baseline test panels (TPs) to validate the accuracy of our computational fabrication process. Following the real-world expectations, we select the following test panels of roughly the same size and shape, but with different curvature properties: Panel TP1 with a positive Gaussian curvature K ranging from 2.72 to 4.89; panel TP2 with a positive Gaussian curvature K greater than TP1, where K is in the range of 4.33 to 20.71; panel TP3 is saddle-shaped, exhibiting negative Gaussian curvature, with K ranging from −12.12 to −0.80; panel TP4 featuring a sign change in Gaussian curvature, with K ranging from −3.78 to 3.76. In Figure 8, we illustrate the progression of the optimization and the accuracy of the final physical mold surface. Each false-color image shows the deviation of the simulated or laser-scanned membrane's shape from the target panel shape. The color encodes the distance from red, indicating a large deviation, to blue, indicating a good fit. The first row shows the deviation of the simulated membrane shape generated by using the boundary curves obtained from the Weingarten surface from the target shape. The rows 2 to 5 show the gradual improvement of the membrane shape during the optimization process.

As more optimization steps are taken, the mold's surface gradually converges to the target panel shape. In row 6, we compare laser scans of the actual physical mold surface to the target panel shape. The results show excellent agreement with the target shapes, with total mean errors ranging from 0.1% to 0.27%. Row 7 shows the integrated L squared distance vs. the number of optimization steps (blue curve indicates the mean error across the panel, the orange curve indicates the mean error at the panel boundary), and in row 8, we plot the stacked Kernel Density Estimate (KDE) of the distance-to-target-panel distribution. As the optimization converges, both the upper bound and the variance of the L squared distance distribution decrease.

Facade Prototype

In this section, we showcase a facade composed of panels fabricated with our flexible mold. The facade is specifically designed to be significantly more challenging than real-world examples, as our facade is engineered to incorporate three challenging geometric properties to realize during fabrication: positive and negative Gaussian curvature, a wide range of Gaussian curvature in both positive and negative extremes, and almost developable panels. A part of the facade is segmented into 9 panels, arranged in a 3 × 3 array. Out of the 9 panels, 7 panels have mixed curvature with a distinct range of Gaussian curvature distribution, with one panel being almost developable. As shown in Figure 1 and 7, the surface continuity of the fabricated facade is maintained, and it is clearly perceivable. The scale of the prototype is 1:10 compared to full-scale architectural facade panels. We anticipate that scaling up by a factor of 10 will not present significant challenges. Theoretically, the membrane's thickness and material properties can be adjusted to accommodate larger panels, since the membrane thickness and stiffness can be increased proportionally to the panel size to maintain the same panel weight-to-pressure ratio.

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Fig. 1: Biopolymer Pavilion at the Nordbau Neumünster 2022

DIGITAL CULTURE – FROM DESIGN TO PRINTED STRUCTURES

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Abstract

Integrating design and build projects with research inquiry is a fundamental component of our architectural education framework. Our approach is inherently interdisciplinary and aims to establish a computational continuity from design conception to digital fabrication. The following two projects–Biopolymer Pavilion and Hexastone Pavilion–illustrate this pedagogical and research. Both projects serve as integrated teaching and research experiments, culminating in full-scale architectural demonstrators.

Biopolymer Pavilion

The Biopolymer Pavilion represents a student-led design-and-build research project exploring sustainable materials and large-scale additive manufacturing (LSAM) with biopolymers. The project examined printability, structural performance, aesthetic expression, and environmental sustainability of a biodegradable composite material consisting of lignin and timber fibres.

While the material's biodegradability ensures environmental compatibility, it also limits resistance to weathering and fire. The thermal printing process employed granulated UPM Formi on a heated printing bed, necessitating controlled laboratory conditions. The resulting pavilion geometry–a segmented, double-curved freeform surface–demonstrates the system's adaptability to complex architectural applications, such as optimized façade systems. The project thus transitions from material experimentation to architectural feasibility, considering site, time, cost, and functional constraints.

Design Process and Geometry

The construction system allows the realisation of freeform geometries through additively manufactured biopolymer segments. Given the constraints of LSAM, the digital workflow subdivides the overall geometry into coplanar, printable segments. The design emphasizes rapid, reversible assembly through horizontal and vertical tensioning using flax cords. In subsequent tests the flax cords prove to be ineffective to the structural performance and are omitted.

The demonstrator consists of two configurations:

(1) A double-curved freeform structure with overhangs, composed entirely of unique elements demonstrating geometric flexibility; and

(2) Single-curved walls composed of identical elements, emphasizing system modularity.

Fig. 2: Masterthesis Anna Prell: Application of
3D printed biopolymer structure

A Rhino Grasshopper definition subdivides the surface parametrically in the U and V directions, creating quadrangulated segments that adapt to local curvature–smaller quads in tight bends and larger ones on shallow curves. Each quadrilateral is subdivided into a rhombus and further refined into curved segment geometries.

While the system can theoretically apply to any freeform surface, practical limitations are imposed by printing bed dimensions, nozzle size, path thickness, and material behaviour. Overhang limits and path continuity are crucial to prevent weak seams and ensure material cohesion.

The double-curved demonstrator represents a section of a helical form with varying radii (3–6 m), subdivided into 25 horizontal rows (25° each) and six vertical columns (7.5° each), accumulating 150 unique segments with an approximate diameter of 21 m. The single-curved walls derive from circular arcs (45°, ø 10 m), standing 2.4 m high, each comprising 96 identical segments (60 × 30 × 10 cm) inclined 2° for connection stability.

Production Process

Component and material testing is performed in collaboration with an industrial partner. The full-scale demonstrator–comprising 246 segments, plus additional furnishings (one desk and eight chairs)–was fabricated over a three-week period by students at the premises of the industry partner.

To maximize printing efficiency, up to eight segments are printed simultaneously using optimised toolpath sequencing. The extrusion speed is finely tuned to balance layer adhesion and surface quality, with reduced speeds at transitions and sharp curvatures. Precise temperature control minimises surface staining.

Each segment requires approximately 15 minutes of print time, resulting in 66 hours of machine operation. The workflow includes: verifying bed temperature, loading G-code, monitoring initial adhesion, maintaining material feed, and removing printed components. Post-processing includes drilling bolt holes, correcting imperfections, and sanding surfaces.

Fig. 4: Construction of the Biopolymer Pavilion

All 150 unique and 96 standard elements are labelled and systematically organized for transport and on-site assembly.

Application to Practice: 3D-Printed Additive Extensions for Urban Densification

The growing shortage of affordable housing, coupled with the urgency of the climate crisis, demands innovative strategies for sustainable urban densification. The integration of digital design, material innovation, and fabrication technologies plays a pivotal role in addressing these challenges.

Within this context, computational design and 3D printing enable the development of functionally and aesthetically optimised architectural systems. By leveraging artificial intelligence and data-driven design, new relationships and morphological possibilities emerge during the conceptual phase.

Anna Prell's Master project proposes a two-level approach to vertical urban expansion. Additive extensions are conceived as independent 3D-printed roof structures placed atop existing buildings, minimizing structural intervention in the existing fabric.

The roof extensions are designed as optimised, lightweight shells composed of 3D-printed modules. Dormer-like openings are introduced as parametric variables to enhance habitability and accessibility, while outwardly inclined gable walls improve structural stability and daylight penetration. This approach demonstrates how digital fabrication and sustainable materials can redefine architectural practice and contribute to a more adaptable, resource-efficient urban future.

Fig. 3: Hexastone-Pavilion at the Nordbau Neumünster 2023

Fig. 4: Hexastone Pavilion under construction: temporary formwork supporting the shell before removal

Hexastone Pavilion

The Hexastone Pavilion emerges from a collaborative Master's-level research and teaching project that brings together students of architecture and structural engineering. The project investigates the potentials and challenges of 3D-printed concrete elements for structural shell construction at an architectural scale. Beyond the practical realisation of the demonstrator, the project focuses on three interrelated aspects:

(1) the computational design and form-finding process;
(2) the geometric rationalisation of the shell structure; and
(3) the generation of digital fabrication data. While initial design and experimentation are conducted in the university laboratory, the final elements are fabricated in cooperation with an industrial partner.

Design and Form Finding

The overall shell geometry is developed through a computational form-finding process based on a simulated hanging catenary network under self-weight conditions. The simulation employes Kangaroo, a physics engine within Rhino Grasshopper, which uses a dynamic relaxation algorithm based on Hooke's Law. The algorithm iteratively adjusts the geometry of the network to achieve equilibrium between internal and external forces, including elasticity, degrees of freedom, and gravity. The resulting geometry is a synclastic, double-curved continuous surface determined by the selective fixation of boundary nodes and the calibration of damping and elasticity parameters. Because the simulation neglects bending stiffness in its elements, the resulting equilibrium form exhibits curvature defined solely by tension–producing edge arcs but no anticlastic behaviour.

Material Characterisation

The project employs Sikacrete-751 3D, a commercially available, ready-mix 3D printing concrete. The material's flexural and compressive strengths are empirically validated following DIN EN 196-1:2016-11 and DIN EN 1015-11:2020-01. Standardised specimens (160 × 40 × 40 mm) are cut from printed samples and tested. Flexural strength is determined under a continuous loading rate of 50 N/s, while compressive strength tests use a 40 × 40 mm steel transfer plate on the split halves from the flexural tests.

Printing Process

Each element is fabricated on a flatbed printer, necessitating the polygonal tessellation of the synclastic shell surface to create planar elements with inclined edges. While the overall dimensions of the printed stones closely match the digital model, the finite thread thickness and material deposition produces characteristic rounded corners and visible material accumulation at the start and endpoints of each printing path.

The aspect ratio of the stones varies according to their position within the pavilion geometry. Stones with an aspect ratio near 1 are printed using concentric circular toolpaths from the perimeter toward the centre. The spacing between paths correspond to the extrusion width, determined by nozzle size and material composition. For elongated stones (aspect ratio < 1), the toolpath is adapted: the perimeter is printed first, and the interior filled with a meandering pattern to prevent excessive overlap or gaps.

The nominal printing accuracy is ±5 mm; however, due to the viscosity of the material and gravitational compression, deviations tend to be observed in the positive range. Sharp digital corners translate into rounded physical edges with radii approximately equal to the extrusion width.

Assembly and Disassembly

The pavilion rests on standard concrete block foundations measuring 60 × 60 × 60 cm. A temporary wooden support structure is preassembled on site, precisely aligned to the intended final geometry, and connected using removable joints to facilitate its later disassembly.

Once the support frame is in place, the Hexa-stone elements are manually positioned, starting from the foundation blocks and progressively assembled upward toward the apex. The balanced distribution of loads during assembly proved essential, as each stone exerts substantial point forces on the temporary structure. Any uneven loading across the three sides results in undesirable deformations of the support frame–an effect that is carefully monitored and prevented throughout the construction process.

The Hexa-stones themselves are connected by filling the gaps with no adhesive mortar to sustain the compression only connection between the elements and to allow for non-destructive disassembly.

Fig. 1: Veneer lattices used as structural reinforcement for mycelium composites

GROWING WITH ROBOTS: FROM VENEER PRINTING TO MYCELIUM MANUFACTURING

Towards biobased robotic fabrication through additive and growth-driven design

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Abstract

Additive manufacturing has opened new pathways for sustainable construction, yet most applications remain limited to conventional, static materials. This essay explores an expanded material palette for robotic fabrication, moving from timber-based additive processes toward living, biobased systems with mycelium. By integrating growth as a fabrication principle, we demonstrate how digital design, robotic control, and biological processes can converge to produce hybrid, reinforced structures that are both engineered and cultivated. Timber offers precision, structural performance, and scalability, while mycelium introduces adaptability, acoustic performance, material circularity, and the potential for self-organization. Together, they suggest a shift from "printing objects" towards "growing constructions." Beyond technical methods, this essay reflects on the cultural and industrial implications of incorporating living matter into manufacturing, where fabrication is no longer only about processing material, but also about designing with time and growth conditions to create custom-grown material characteristics.

Introduction

At the Department of Experimental and Digital Design and Construction (EDEK) at the University of Kassel, we have developed a spectrum of additive manufacturing methods for continuous timber yarns and veneer bands, enabling the fabrication of hollow components, 3D-printed forms, and three-dimensional lattice structures. Unlike natural fibre composites, which have very good structural properties but often require energy-intensive production and a high resin content of over 50% [1], engineered timber products have a low carbon footprint, offer comparable mechanical properties and a low adhesive content of 2–15% [2]. In this context, our research in wood-based additive manufacturing investigates how local, renewable timber resources can be transformed into acoustically and structurally intelligent architectural components through the integration of digital design, robotic fabrication, and material knowledge.

In recent research, these investigations have been extended to include growth-driven additive manufacturing with mycelium, where biological processes are harnessed as an active part of the fabrication logic. By combining fast-growing local species, such as willow rods, with robotic winding, 3D printing, and lattice formation techniques, and integrating adhesive-free joining methods, we have created a pathway toward hybrid constructions that merge engineered and living materials. This essay traces this trajectory, from material design and creation with willow rods, through the development of 3D winding [3] and printing methods with continuous veneer edge bands [4], to ultrasonic welding and growth-based fabrication with mycelium composites [5][6]. In doing so, it reflects on how the convergence of material innovation, robotic control, and biological growth can expand the possibilities of architecture, transforming fabrication from the mere shaping of static materials into a collaborative process incorporating time, growth, and material behavior.

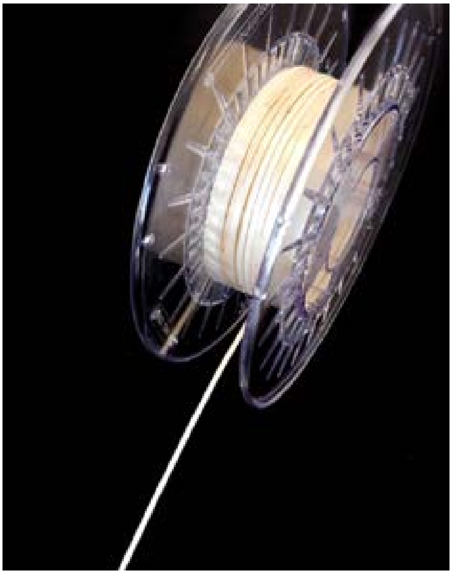 

Fig. 2: Continuous wood monofilament made from willow rods (Salix americana). The 1–2 m rods are split, homogenized to a standardized rectangular cross-section, and joined through angled scarf joints with adhesive bonding.

Wood Yarns for Weaving and Additive Manufacturing

In 2017, the University of Kassel initiated the interdisciplinary research cluster TETHOK, bringing together researchers across architecture, engineering, and material science. The shared aim was to rethink the role of timber in digital and robotic fabrication by developing continuous solid-wood filaments, a material innovation that could bridge the gap between textile and timber processing. The monofilament is a continuous, solid-wood thread that behaves like a textile semi-finished product while preserving the inherent material properties, aesthetics, and sensory qualities of natural wood (Figure 2).

Building on this premise, the research team developed continuous threads from locally sourced willow strips, a material traditionally associated with handcraft and basketry. Willow is a fast-growing resource that regenerates within roughly one year, making it a renewable, locally available material ideally suited to biobased manufacturing [7]. The strips were homogenized and joined into long, flexible filaments capable of weaving, winding, and robotic placement. The joining of filaments into surfaces and structures was explored in multiple ways: without additional binders for weaving [8]; with additional timber adhesives for placement [4] (Figure 3); and through integration into a polymer matrix [9]. The resulting system enabled the fabrication of gradable wood–composite surfaces in which stiffness, strength, and tactile expression could be locally tuned [10].

To translate this concept into robotic production, the research extended toward additive manufacturing with continuous wood filaments, culminating in a European patent application in 2019, which was officially granted in 2024 [11]. This milestone confirmed the technical novelty and feasibility of the approach, positioning wood as a viable feedstock for robotic and additive fabrication processes that remain grounded in local, renewable, and culturally embedded resources.

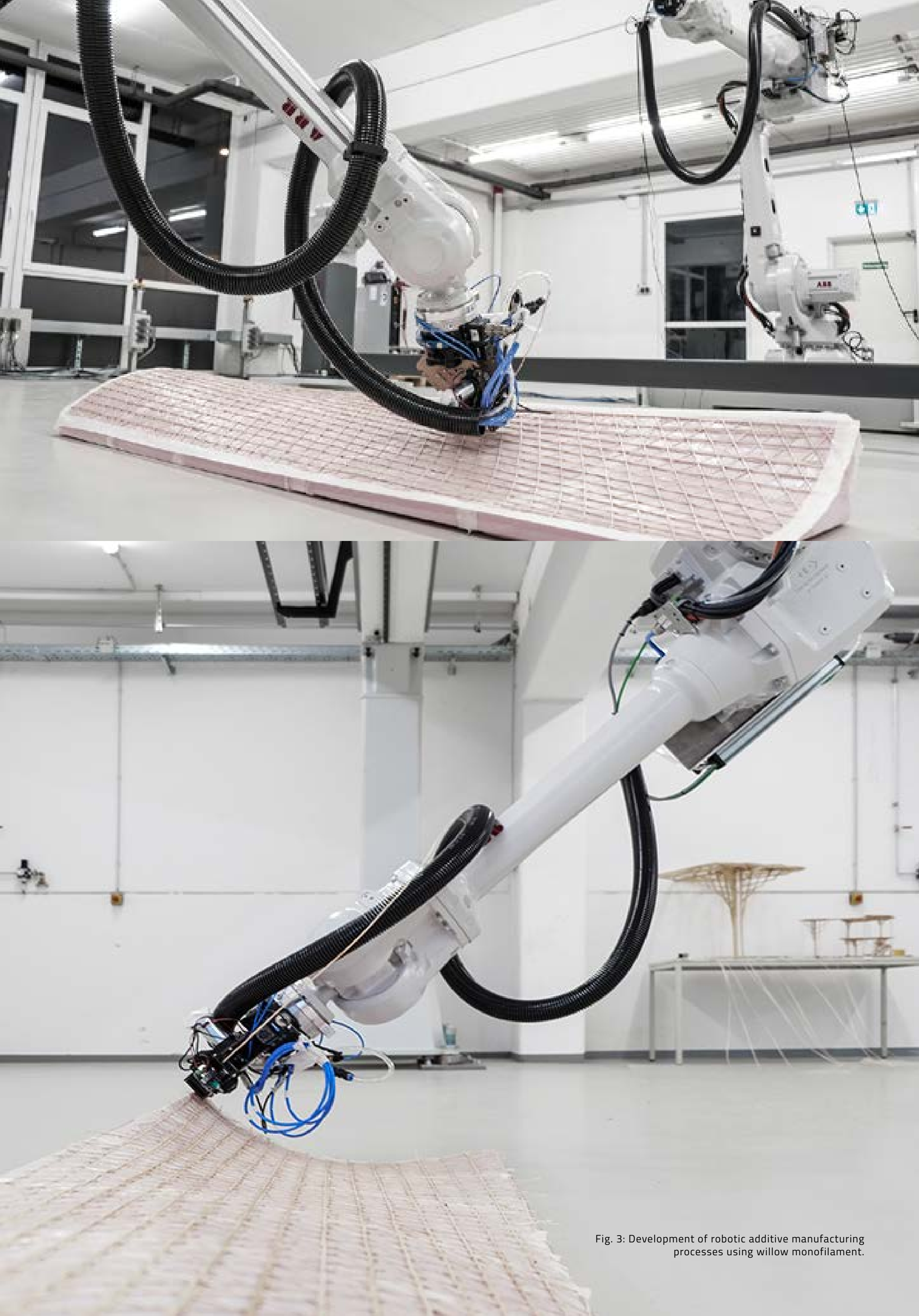

Fig. 3: Development of robotic additive manufacturing processes using willow monofilament.

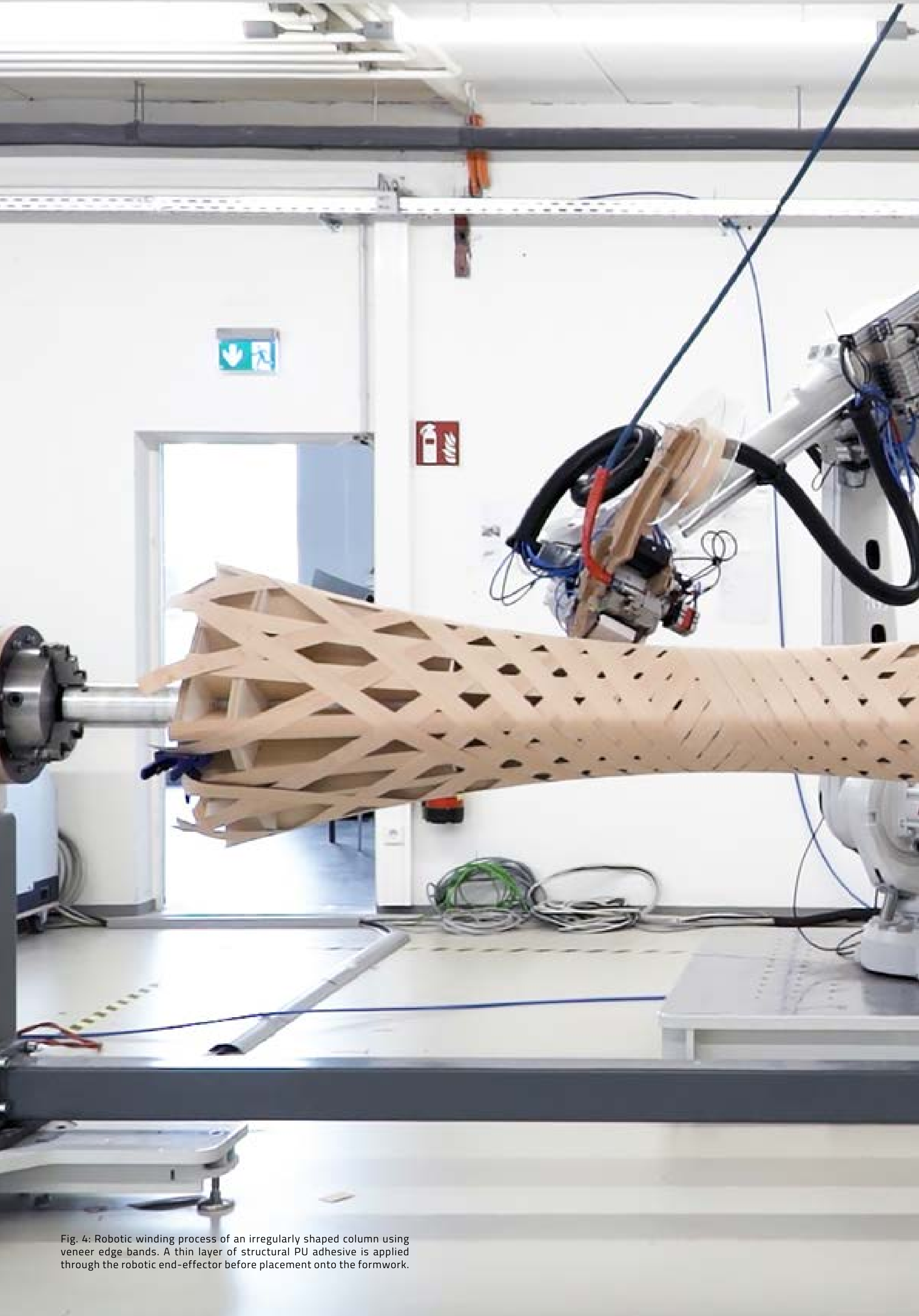

Fig. 4: Robotic winding process of an irregularly shaped column using veneer edge bands. A thin layer of structural PU adhesive is applied through the robotic end-effector before placement onto the formwork.

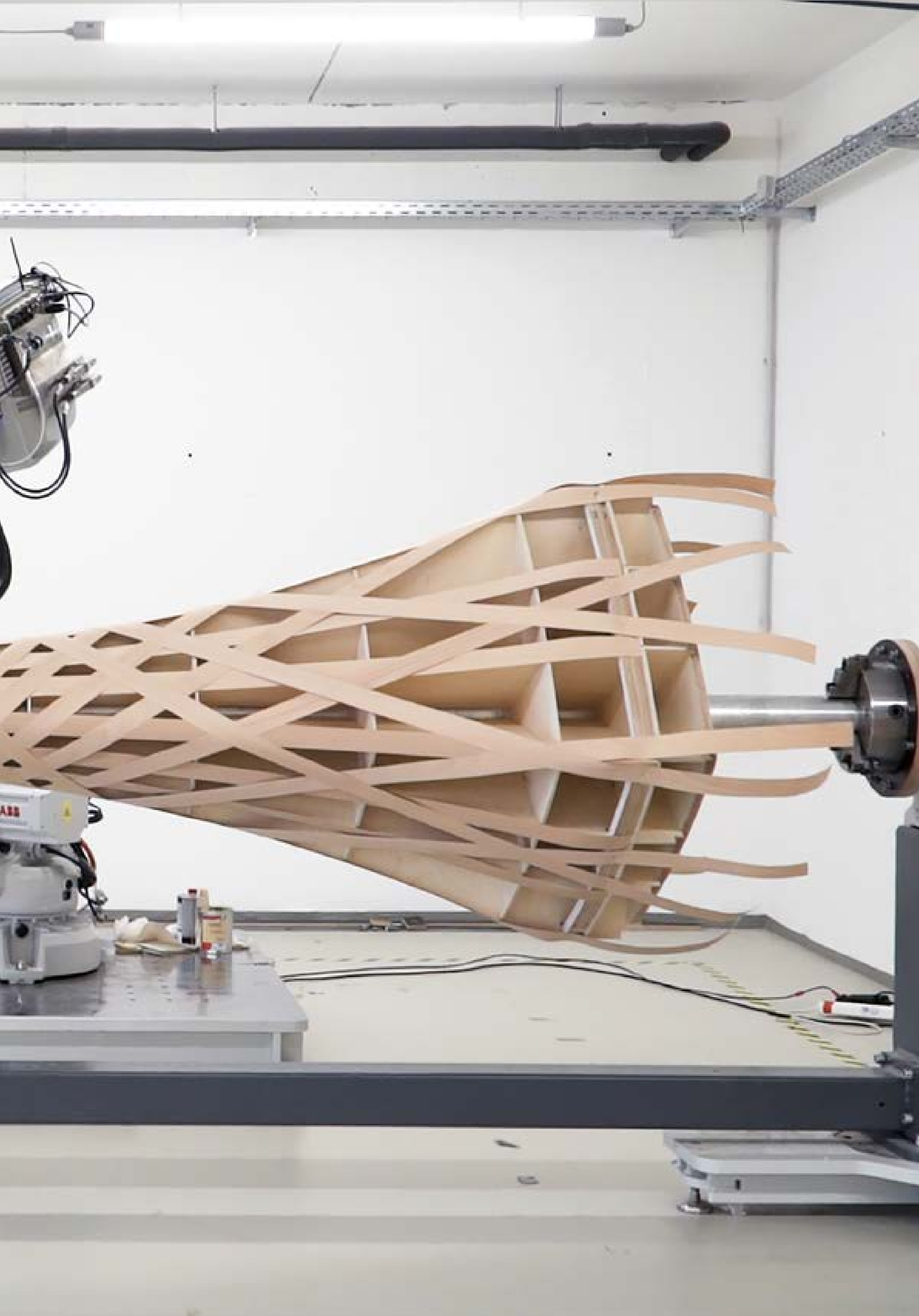

Fig. 5: Beech wood veneer edge banding (48 mm x 0.5 mm) with a cellulose fleece backing and finger jointing

Veneer-based Additive Manufacturing

Through a series of subsequent research projects, we expanded our investigation of bio-based additive manufacturing to include an industrially available material: veneer edge bands. Commonly used in the furniture industry as edging, these thin wood strips can be produced in continuous rolls up to 200 meters by finger-jointing individual segments and reinforcing them with a thin cellulose fleece (Figure 5). Their structural capacity, dimensional stability, flexibility and availability make them an ideal resource for experimental additive manufacturing with timber. The following sections explore 3D winding, 3D printing and the fabrication of 3D lattices with veneer bands, each of which involves different binding and manufacturing methods.

3D Winding

In an initial study, we examined the robotic winding of small profiles with diameters of approximately four centimeters, exploring both circular and square geometries [12]. This early research served as a testbed for material handling, robotic toolpath generation, and adhesive performance. Building on these insights, we later won a national competition to realize a full-scale architectural prototype: a 7 × 7 m roof structure composed of modular, wound veneer components supported by four mushroom-shaped columns that were structurally anchored to a modular slab [3]. The prototype demonstrated that veneer winding could scale from experimental fabrication to spatial construction.

For the 3D winding process, we employed structural polyurethane (PU) adhesives characterized by relatively long curing times, an advantage in this context, allowing uninterrupted multilayer robotic placement of the veneer strips. Traditionally, such components would require hot pressing or vacuum bagging for curing, processes that are both energy- and time-intensive. Instead, we developed an approach in which the robot maintains continuous tension during winding, applying controlled compression directly through the process [13]. This eliminates the need for any post-compression or external pressing, reducing both fabrication energy and complexity.

This research demonstrated that robotic 3D winding enables a new class of lightweight, materially efficient timber structures with minimal tooling. Building on these insights, we are currently developing WoodWind+, an ultra-light building system designed for architectural extensions, such as roof additions and lightweight infills, that combine high structural performance with low environmental impact (Figure 6/7).

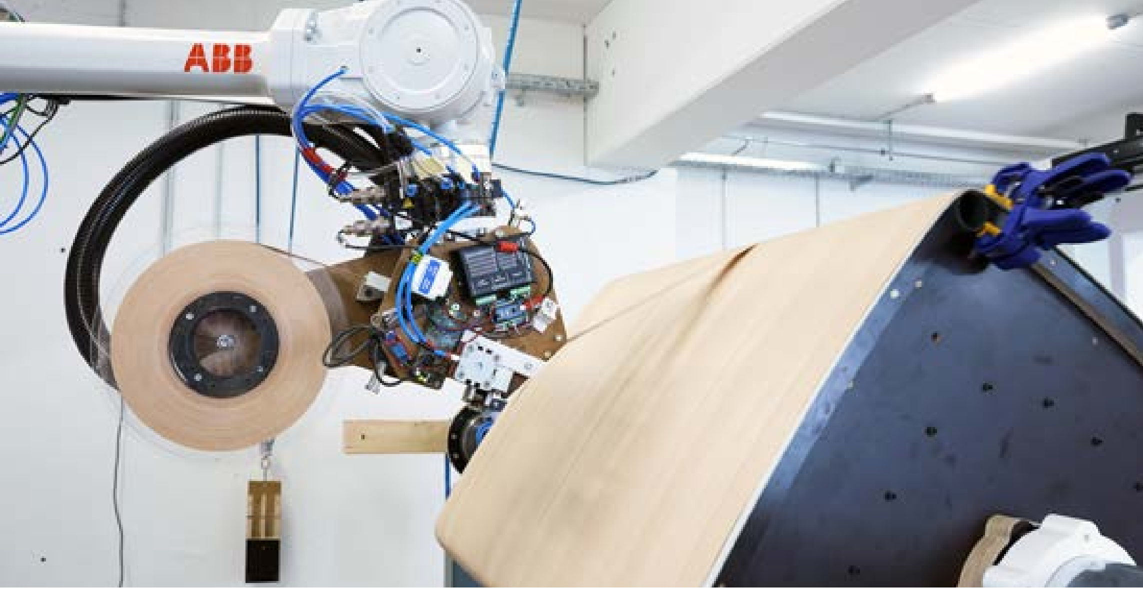

Fig. 6/7: Wood winding of ceiling components for an ultra-light building system designed for architectural extensions.

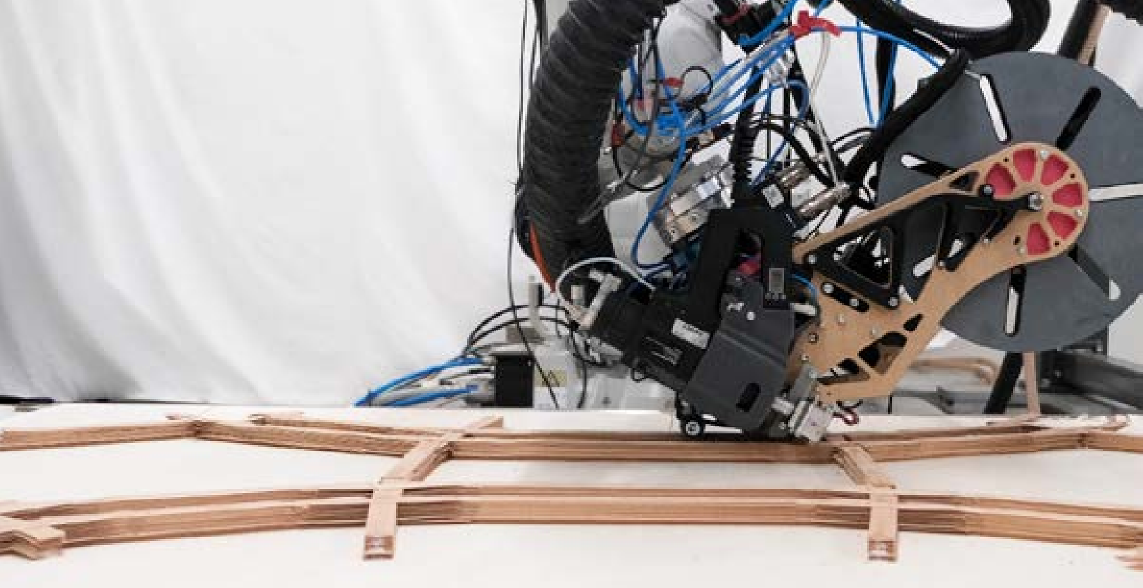

Fig. 8: Robotic 3D printing process with veneer edge bands and fast-curing adhesives.

3D Printing

While additive manufacturing has advanced rapidly across many material domains, large-scale 3D printing methods using wood remain rare. Existing processes typically rely on pulverized wood particles bound with synthetic resins or polymers [14], a strategy that sacrifices the material's inherent structural and mechanical properties. In contrast, our research explores additive fabrication methods that preserve wood's natural continuity by using willow monofilaments and veneer bands as continuous feedstocks.

Building on the experience gained through the TETHOK cluster, we developed a robotic 3D printing process that operates as a continuous deposition system, in which the wood filament is only cut when directional changes occur. This method allows the integration of geometry, material behavior, and process logic into a unified fabrication system. To enable design directly within the constraints of the material and process, such as maximum overhang angles, build heights, and minimal bending radii, we created computational design tools that embed these parameters, ensuring that resulting geometries are inherently fabricable. The continuous nature of the process requires adhesives that cure rapidly, establishing an initial bond with each applied layer. We investigated a wide range of chemical and natural adhesives, including contact adhesives, UV-curing systems, and polyurethane (PU) hotmelts, as well as biobased alternatives such as glutin glue, casein, and chitosan. The fabrication system is fully automated, employing stepper motors for filament extrusion, pneumatic devices for cutting, and adhesive application through extrusion.

The ongoing DFG-funded project Wood3DPrint advances this work through a layer-based lamination approach using a reactive polyurethane adhesive, allowing higher deposition rates and improved inter-layer adhesion. Current research focuses on curved and planar slab structures that demonstrate the architectural potential of this method for lightweight wall and slab systems (Figure 8). These prototypes suggest new possibilities for biobased additive construction, where structural performance, form, and fabrication logic are informed directly by the material itself.

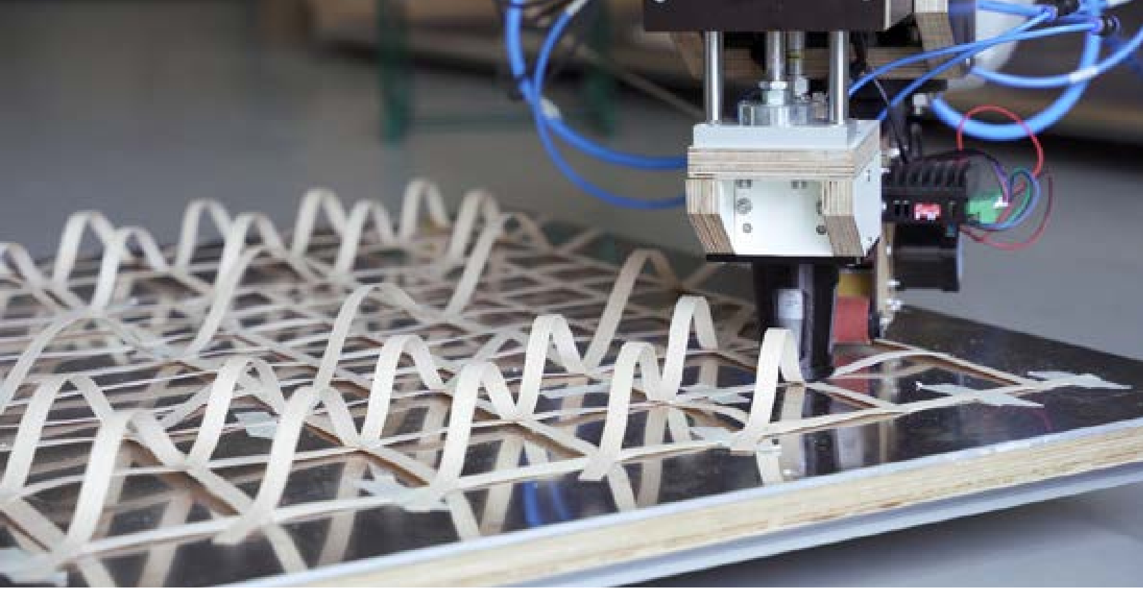

Fig. 9: Robotic fabrication of three-dimensional veneer lattice systems using ultrasonic welding.

3D Lattices and Ultrasonic Welding

In addition to filament and veneer-based additive processes, we explored three-dimensional lattice structures that exploit the bending-active properties of veneer edges. These lattices are generated by connecting two offset 2D grids with a wave-curved interlayer, implemented in a continuous robotic fabrication process. This approach allows complex, open-work geometries to be produced efficiently while maintaining material integrity and structural performance.

The robotic workflow for creating 3D lattices builds upon sequential layer deposition. After printing the first 2D lattice, the process is repeated for the intermediate wave-curved layer, during which additional veneer is extruded to generate the lattice's vertical dimension. Once the first two layers are completed, the partially finished lattice is removed from the print bed, and a second 2D lattice is printed using the same method. The first layers are then positioned atop the second lattice and connected, resulting in a three-dimensional lattice with uniform height and precise geometrical control (Figure 9).

To achieve fully biobased lattice connections, we developed a new joining method using ultrasonic welding. This approach leverages the inherent lignin in wood, which is activated by high-frequency vibrations, eliminating the need for adhesives. The development process was informed by prior research in friction welding of larger timber elements at EPFL [15] and ultrasonic welding of thin cellulose sheets [16]. Additionally, we partnered with specialized ultrasonic welding companies to perform the required studies, testing welding parameters, vibration frequencies, and energy input to optimize bond strength, precision, and repeatability for thin veneer strips. These industrial collaborations were critical in translating lab-scale techniques into a scalable, reliable robotic welding process, enabling the production of fully biobased, structurally robust lattice systems.

Fig. 10: Veneer lattices used as structural reinforcement for mycelium composites.

Growth-based Additive Manufacturing with Mycelium

Since 2020, our research has focused on growth-based design and manufacturing methods with mycelium, exploring how this fast-growing, biologically active material can expand the possibilities of biobased construction. Unlike timber, which requires 35–70 years to reach maturity for building applications [17], mycelium can develop into complex forms within weeks, making it one of the fastest renewing building materials. In addition, mycelium exhibits excellent acoustic and insulation properties and is hard to inflame [18], positioning it as a versatile candidate for architectural applications [19].

We identified interior fittings for offices as a particularly promising application, due to their relatively short service life of 5–7 years and the ecological limitations of conventional materials [20]. Many composite products permanently bond biodegradable materials such as wood fibers with non-biodegradable adhesives, preventing recyclability and increasing the overall ecological footprint. Currently, the selection of biobased, high-performance, and affordable alternatives is limited, highlighting the potential for mycelium-based solutions.

A key challenge, however, is the limited mechanical performance of mycelium, comparable to foams such as EPS, which, until now, has restricted applications to small panels and short spans of up to 60cm [21]. To overcome this limitation and enable broader architectural use, we developed a reinforcement strategy inspired by reinforced concrete. The approach employs the previously described 3D lattices as internal scaffolds, which transfer compression and tension load. The mycelium grows around and within the lattice, creating a composite structure (Figure 10). Ganoderma lucidum, a fungal species known for its ability to bond with timber, was used as mycelial culture, in combination with hemp hurds as the primary substrate. Maple veneer performed well for both ultrasonic welding and mycelium adhesion, making it a suitable material for the reinforcement lattices. In the HOME I project, we further developed this concept of additive manufacturing for large reinforcement lattices, and optimized the mycelial growth processes, producing several large-scale research demonstrators [22].

In the subsequent HOME II project, we advanced toward a robotic multi-material deposition process, expanding the substrate palette to include sawdust, which allowed for denser, structurally and acoustically optimized composites. The mycelium substrate required a material delivery method to the robotic end-effector that would minimize contamination, reduce manual handling, and gently transport the delicate fungal

Fig.11: AM process with mycelium substrates, combining sawdust-based and hemp-based mixtures for acoustic and structural customization.

network without damaging it. Therefore, we developed a robotic end-effector based on a cyclone separator comprising two pinch valves and an intermediate material reservoir. Centrifugal force separates the mycelium substrate from air, collecting the material in a hopper. By controlling the pinch valves, the robot can suck material into a reservoir in the end-effector and then deposit it. This system enables a semi-continuous, multi-material deposition, opening possibilities for customized material properties, adaptive growth-deposition cycles, and interactive fabrication during growth (Figure 11/12). We also conducted research into the automated densification of the material in formwork using vibration experiments.

In the current Momentum project, Robotic BioConstruction, funded by the Volkswagen Foundation, the goal is to further develop these processes towards large-scale circular fabrication in architecture. Therefore, we are currently setting up an integrated biolab as an extension of our existing DFG Robotic Architectural Production instrumentation facility. In initial studies, the integration of robotic kinematics and biomaterial joining was investigated [23][24].

Through these innovations, we have established a scalable, automated, and flexible approach to growth-based additive manufacturing with mycelium, combining biological growth, structural reinforcement, and robotic fabrication to produce components with tunable material properties for architectural applications.

Conclusion and Outlook

This body of work demonstrates a continuous evolution from timber-based additive manufacturing toward growth-based fabrication with living materials, revealing new ways to integrate material, form, and process in architecture. Beginning with continuous wood filaments, we explored how traditional craft techniques can be reinterpreted through digital design and robotic fabrication to produce gradable, high-performance timber surfaces. Veneer-based winding, 3D printing, and lattice structures extended these ideas, enabling lightweight, structurally optimized components and introducing fully biobased joining methods such as ultrasonic welding.

Across these additive manufacturing approaches, it is evident that no single joining or bonding strategy can serve all material and process conditions. Instead, each technique requires specific binders, curing systems, and application technologies, calibrated to the constraints of deposition speed, geometry, and material behavior. From slow-curing polyurethane systems in robotic winding to reactive hotmelts and UV-curing adhesives in 3D printing, and finally to adhesive-free welding and biological

Fig.12: AM process with mycelium substrates, combining sawdust-based and hemp-based mixtures for acoustic and structural customization.

bonding in growth-based systems, the evolution of fabrication also entails an evolution of material binding logics, moving from chemical adhesion to physical fusion and, ultimately, to biological integration.

Building on this foundation, mycelium-based additive manufacturing represents a conceptual and material shift: here, the material itself grows into form, guided and reinforced by robotically assembled timber lattices. By combining living substrates, multi-material deposition, and structural reinforcement, these methods overcome mechanical limitations and open possibilities for interactive, customizable, and regenerative architectural components. Fabrication thus transforms from the mechanical processing of inert matter into a collaborative process with time, growth, and material behavior.

Looking ahead, this research suggests a future in which architecture is designed and constructed in dialogue with living systems. Hybrid strategies combining timber and mycelium, coupled with adaptive robotic control and responsive material design, may lead to high-performance, recyclable, and environmentally attuned structures. Beyond technical innovation, this work invites a rethinking of construction itself, not as an act of assembly, but as a continuum of growth, transformation, and interaction, where sustainability, material intelligence, and architectural expression converge.

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Fig. 1: A segmented column serving as an illustrative to showcase different outcomes of surface post-processing

FUNCTIONALIZING CERAMIC BUILDING COMPONENTS THROUGH AM

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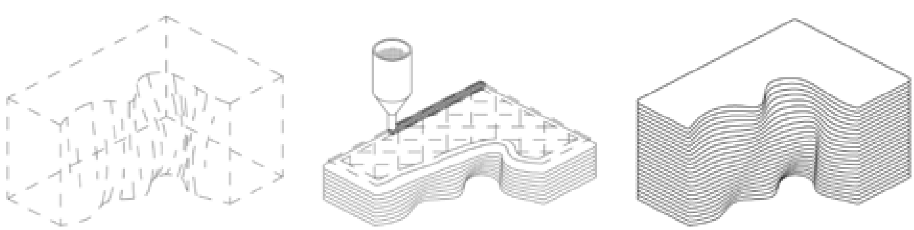
Abstract

Much attention is given to in-situ production of concrete AM and the ful-scale creation of steel-structures, which already advance into the market. But what if there was a material, that does not allow for either of it? One of mankind's oldest construction materials has an indispensable need for a subsequent firing, to achieve is favourable properties. But what is necessary to 3D-print and use ceramic objects in architectural scale? This research looks into what needs to be done to enable an industrial production and how a useful application of such pieces may look like.

Being used for construction purposes since 5.000 BC [1], ceramic components represent one of mankind's oldest building materials. Apart from bricks, other applications such as sewage pipes, roof tiles, flooring and even bathroom ceramics demonstrate the versatility of this material. Even the rise of other materials, such as bricks from aerated concrete or calcium-silicate in the early to mid-1900s, did not replace ceramic masonry, which still remains highly relevant by being used in about 30% of solid constructed residential buildings in Germany [2]. While in their conventional process, bricks are produced trough extrusion only allowing for a 2 ½-dimensional shaping, novel technologies like robocasting [3] allow for a greater geometric freedom [4], colloquially referred to as 3D printing. As in most AM (additive manufacturing) processes, a virtually created geometry is split into horizontal layers, which in turn again are dissolved into paths. By deploying viscous clay material alongside the so-created paths, a geometry is built up line-by-line and layer-by-layer according to this digital model (Fig. 2).

Even though they allow to create a more articulate geometry, AM methods come with a severe economic disadvantage: their process-inherent slowness. While common processes like the aforementioned extrusion are able to create one brick every three seconds, leading to high yields, the speed of Robocasting is depending on several parameters. One of their most influential is the width of the deployed strand, which goes hand-in-hand with the height of each layer. This relationship is known as the print's resolution, which for larger components is often set rather low to ensure an, at least somewhat, short processing time.

Fig. 2: The process of Robocasting from digital model to physical object



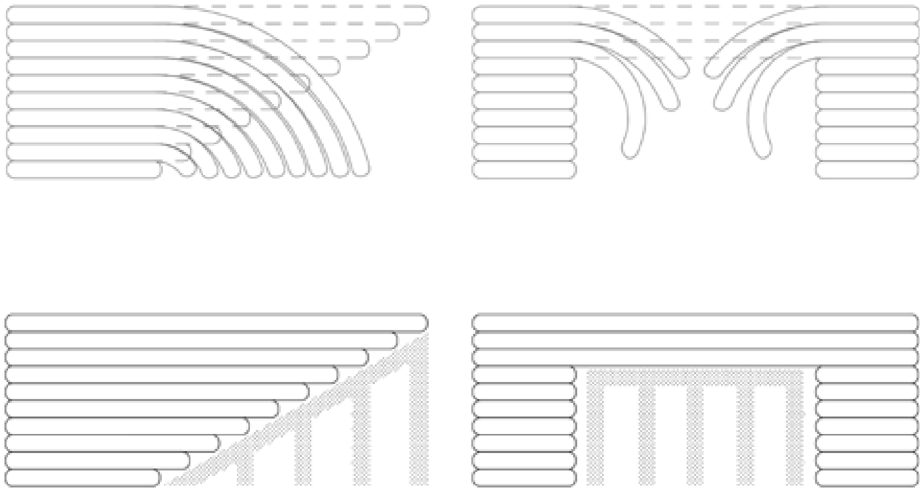


Fig. 3: The lack of a process-inherited support-material limits Robocasting's geometrical freedom

The use of Robocasting may therefore only be justified by producing bespoke ceramic objects whose enhanced functionality requires this enhanced geometrical freedom. Also, it must be noted, that the necessity of a subsequent firing to achieve the desired ceramic properties does not allow for the production of whole structures in-situ, as seen in other materials such as concrete [5], steel [6] or (unfired!) clay [7]. Considering this, the process may only be perceived as complementary to the conventional ways of production, with its use being justified whenever there is a need for enhanced functionality in specific components [8].

When looking at previous research from this field, it is notable that most of the preceding projects can be perceived as design-driven, and only few used the opportunity to add functions [9]. Taking a deeper look at the process itself, certain shortcomings with regards to geometrical freedom for bridging areas or steep overhangs (Fig. 3), as well as the low compatibility of the layered appearance in comparison with conventional ceramic surfaces [4] become apparent. Throughout the past years of research, several strategies to overcome these shortcomings have been developed and evaluated.

Noticeable improvement in terms of overhang- and bridging-abilities has been achieved by researching methods to implement support-geometries. Using support-material, mostly from the same material as it was used for printing, steeper overhangs and wider bridges areas became producible (Fig. 4). Even though none of the found strategies proved to be ideal in all evaluated criteria, a matrix of recommendations has been derived on which strategy to be used depending on the desired outcome [11].

In order to achieve a flush integration into conventional ceramic systems, mostly masonry, a multitude of methods to post-process surfaces has been investigated [12]. Using different treatments, such as filling the gaps in between the strands with slurry or grinding down the surfaces, a harmonized appearance of additively manufactured components has been achieved, that blends into such from conventionally produced ceramic bricks. A case-study, consisting of a column composed from seven segments, each with a wavy, a tessellated, and a flat surface displays the outcome of this research and its applicability and adaptability for contemporary architectural shapes and applications (Fig. 1).

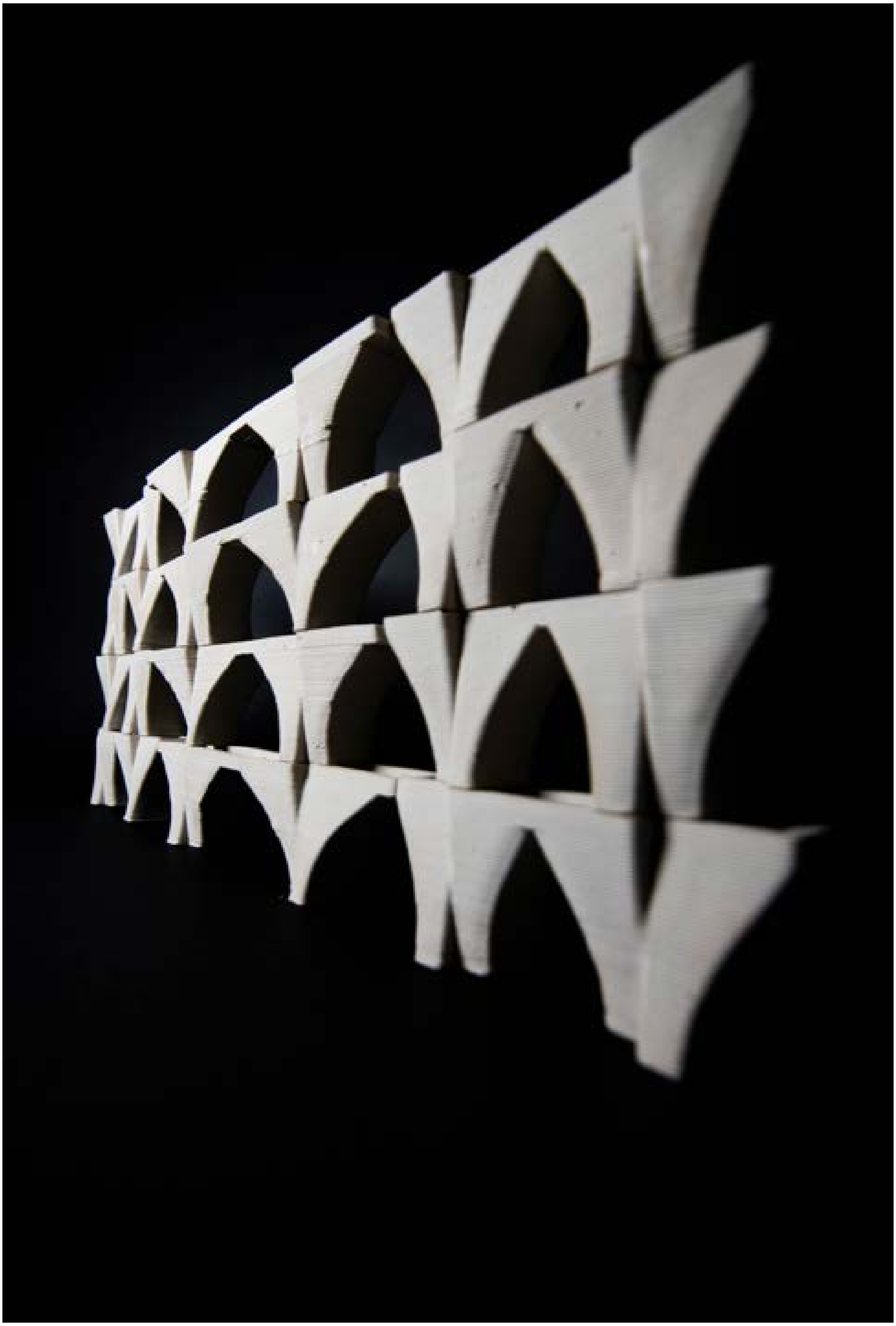


Fig. 4: 3D-Printed ceramic wall components hosting plants to act as a greened facade

Fig. 7: 3D-Printed ceramic wall components hosting plants to act as a greened facade

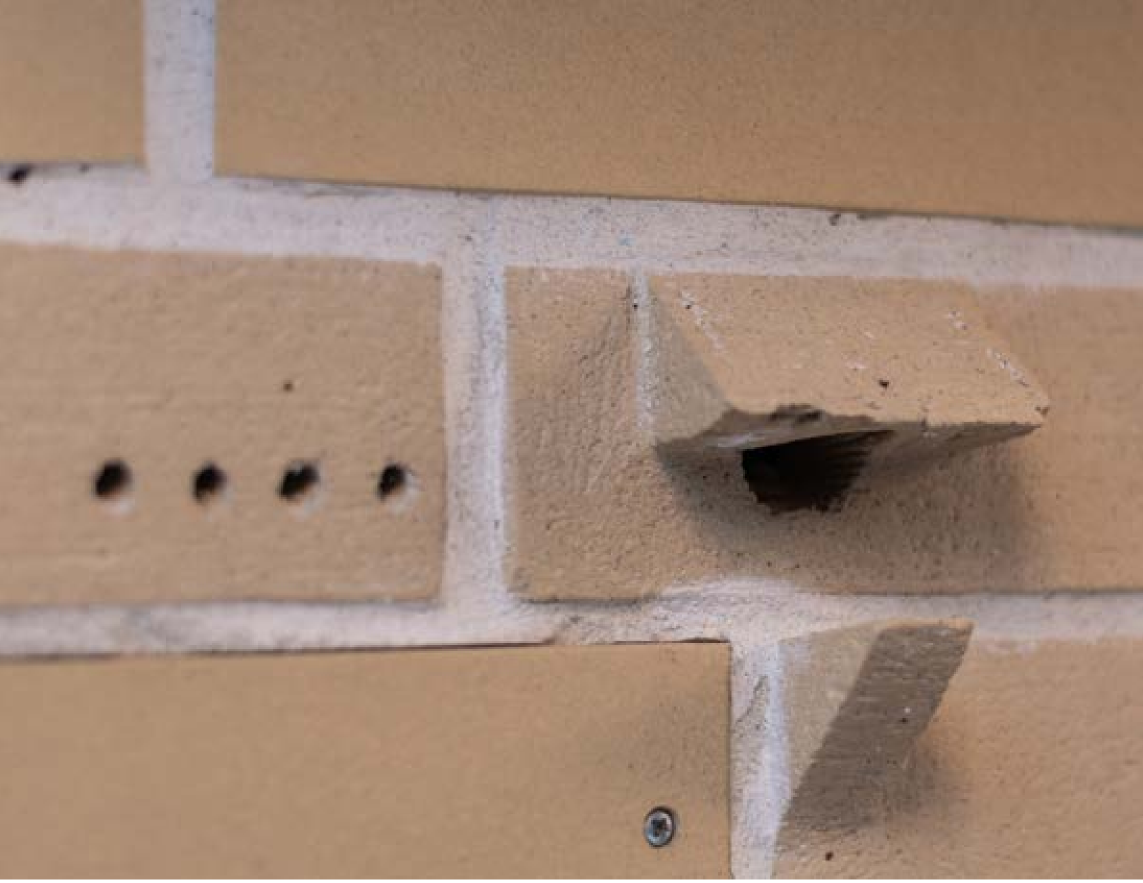


Fig. 5: Opening of a façade-included nesting opportunity for tits

When looking out for application cases of AM Ceramics in the context of functionalization, also several smaller case-studies and projects have been carried out. First, the processes' ability to replace the yet manual process of shaping customized bricks has been evaluated positively [10]. By creating hollow bricks serving as nesting-opportunities for endangered species, Robocasted ceramic components may contribute to the preservation of urban biodiversity (Fig. 5). A total of 3 different nesting-bricks has been produced, each tailored to the specific needs of bats, tits and swallows. Like in the original products, which are already market-available, they flushly blend into double-shell masonry. Within the investigation, also a valuable improvement in terms of processing time was achieved through the consequent application of design for additive manufacturing. By this, it is imaginable, that a worker, who currently takes half a day to manually create one brick, may soon observe a group of printers, which produce many bricks in parallel.

Further, by investigating how undemanding plants, as known from roof greening, can be implemented into double-shell masonry, the technology's suitability to create greened facades has been generally proven [13] (Fig. 7). Trough creating an undulating surface, which slowly morphs from a common running-half brick-bond, pockets in a façade were formed, that store substrate and water and thereby host plants.

Fig. 6: Scanned and recreated frieze on a historic freshwater fountain

Lastly, throughout project researching Robocasting's ability to recreate damaged ceramic components on historic buildings favourable results have been achieved. Besides recreating bespoke, though rather simple bricks as e.g. for lintels, also more articulate geometries have been investigated. By 3D-Scanning well-preserved pieces of a historic, heritage-protected, freshwater fountain, spare parts for damaged ones have been created. By this, not only a methodology of geometry-acquisition and -recreation has been developed, but also research on glazing-technology has been carried out. Admittedly, the researcher never mastered ceramic painting as good as the artisan craftsmen who once created the original (Fig. 6). To conclude, Robocasting may be more perceived as a valuable addition to common processes for shaping ceramic building components, than a full replacement of the common high-yield processes [8,9]. In order to overcome process-related challenges, several counter-strategies have been provided, granting a certain extension of the process window [4,11,12]. Within several case studies, 3D-printed components have proved being suitable for functionalization. However, this mostly happened on a low-tech level like in the mentioned nesting or greening [10,13], as the process only allows for a limited of geometric tolerance.

Nevertheless, creating more geometrically complex ceramic building components through the use of additive manufacturing methodologies proved as feasible and an industrial implementation may be expected in the near future.

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Fig. 1: Growth Pattern Structure

ADDITIVELY MANUFACTURED ACOUSTIC ABSORBERS MADE FROM CLAY

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TU DARMSTADT

Abstract

This project investigates the potential of additively manufacturing acoustic absorbers from clay. The goal is to replace fossil-based sound absorbers by developing a mono-material, sustainable, and acoustically effective structure that does not require additional carrier materials or composites. Since clay inherently exhibits low sound absorption, the improvement of acoustic performance in this study was achieved primarily through the design of geometry rather than the material itself. The developed geometry is based on a growth algorithm that creates complex pore spaces in the inner structure. Methodologically, the approach is supported by computer-based simulations, impedance tube measurements, and reverberation chamber tests that confirm the prediction of the acoustic performance. The developed process chain demonstrates the potential of additively manufactured clay structures as a sustainable alternative to conventional acoustic solutions.

Introduction

Rising urban noise levels have intensified the need for acoustic absorbers that are both effective and sustainable [1]. Although additive manufacturing with clay has recently enabled the construction of entire buildings, the acoustic implications of this technology remain largely unexplored. Conventional sound-absorbing materials are frequently made from acoustic foam, which is fossil-based, resource-intensive, and associated with high CO_2 emissions [2]. While there is a wide range of sustainable and biodegradable acoustic solutions, clay is rarely mentioned. Unlike other biodegradable materials with inherent porosity, clay requires acoustic performance to be achieved through the design of structural and geometric features. This study explores and quantifies the impact of geometry on the sound absorption that can be achieved with 3D clay-printing. It investigates the potential of 3D-printed clay as an acoustic absorber, addressing a critical gap between sustainable material innovation, clay printing and architectural acoustics.

Background

Interest in sustainable sound absorbing materials has increased for years. A wide range of these materials already exist like mycelium-based absorbers [3], plant based shells and different textiles [4]. In contrast to other biodegradable solutions which inherently possess a porous structure, clay does not exhibit this material property.

Its sound absorption performance is therefore very low on the material level [5]. 3D printing clay decreases porosity through pneumatic forces during the extrusion process. Finally, firing almost eliminates porosity, resulting in a lower sound absorption level. Thus, absorption performance must be achieved through the design of its structure and geometry rather than the material itself.

In the context of Additive Manufacturing (AM) in the built environment, clay has emerged as a highly relevant material and is currently being utilized in early pilot projects. The potential of additively manufactured cellular

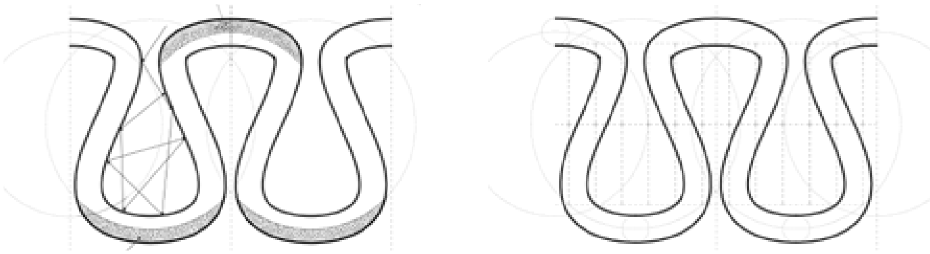

Fig. 2: Alternating Wall System

structures for thermal and acoustic insulation was first highlighted by Rosen in 2013 [6, 7]. In current research of 3D printing it is often used for climate regulation. Gentile (2024) puts forward a 3D-clay-printed surface used as moisture-buffering [8]. For acoustic applications, however, the amount of research remains limited.

Since clay is not a conventional sound-absorbing material, existing research on geometry-based absorbers mainly focuses on other materials. Current research in absorbers is based on other geometric applications. Setaki explores passive destructive interference (PDI) as an absorption principle [9]. PDI absorbers work by directing sound waves along different paths so that they meet out of phase and cancel each other, thereby reducing overall sound energy.

Goidea (2021) developed Meristem Wall – a network of integrated air channels that allow a fluid relationship between inside and outside. Therefore, a high tortuosity level is created [10].

The creation of such complex geometries requires advanced slicing software capable of generating customized toolpaths for clay printing. Eschenbach (2025) developed an experimental slicing software in Grasshopper that was being used within this project [11].

Designing forms for sound absorption

In contrast to conventional absorbers relying on material porosity, our approach aims to generate geometric and spatial porosity in clay structures. A key parameter influencing sound absorption in porous structures is tortuosity, which describes the geometric complexity of pathways within a medium and indicates how much longer or more convoluted a fluid or particle's path becomes compared to a straight line. Consequently, porosity needs to be designed. Our 3D-printed demonstrator absorbs sound on two different scales. Its overall shape is based on alternating convex and concave forms arranged along an undulating path (Figure 2). This design creates resonance-based pockets that allow sound waves to enter and undergo multiple reflections.

The exposed, outer surfaces of the self-supporting system are subsequently equipped with a series of highly porous clay layers. We applied a growth algorithm to 3D print those intricate geometries, (Figure 1). The interaction of the two systems–the resonance-based main structure and the porous surface generated by the growth algorithm–results in an efficient, self-supporting geometry that is acoustically effective, provides high sound absorption performance, and minimizes material usage.

The object is regarded as a self standing interior design object that can be installed in open-space office environments partitioning different areas and improving spatial quality through sound absorption (Figure 4).

Fig. 3: Printed Demonstrator

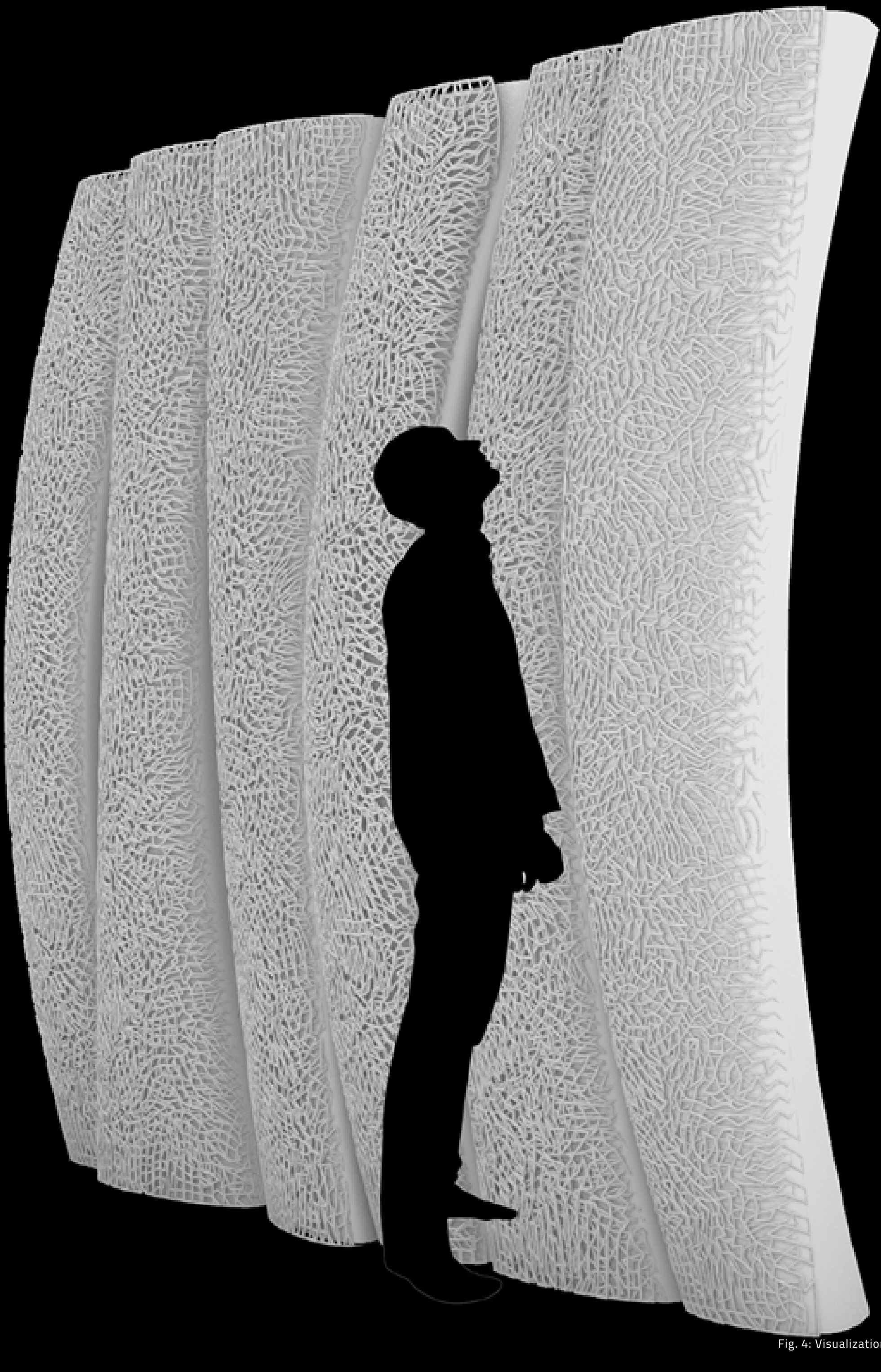

Fig. 4: Visualization

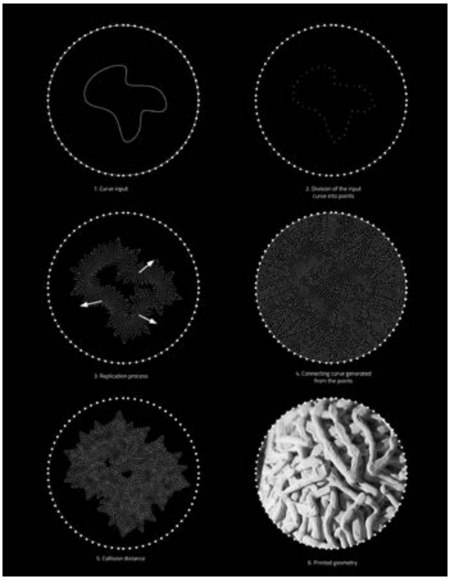

Fig. 5: Growth Pattern Generation

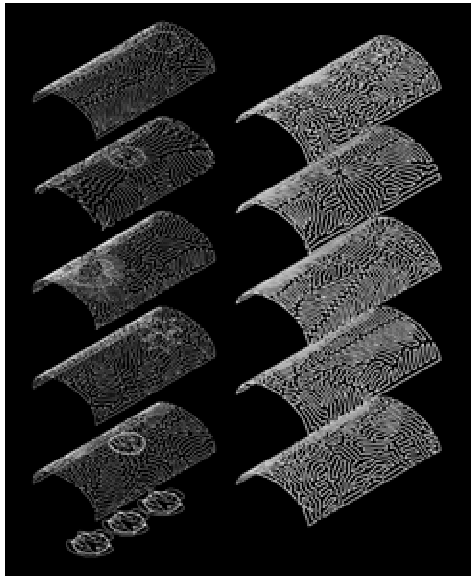

Fig. 6: Syntax

Process chain for 3D-printed clay sound absorbers

In our design two principles of sound absorption appear: The main structure with its alternating pockets and the complex porous space created by the growth algorithm. Our design to fabrication process chain contains the below described elements. exemplified by a research prototype that was designed, analyzed, and fabricated accordingly.

1. Generate 2D canal grid by differential growth algorithm

Within this project, the differential growth algorithm was investigated as a generative design and absorption principle. The process begins with a user-defined series of seed points that are repelling each other.

The resulting points are connected to form curves or polylines with a complex system of branching, continuous channels (Figure 5). Stacking those planar curves with different seed points vertically like floor plates, creates intricate 3D porous spaces. For the curve overlays, multiple input curves were generated from different origins, forming a syntax that alternates between biomorph and symmetrical inputs (Figure 6). This alternating placement provides sufficient support points for every subsequent layer of fragile clay extrusions.

The printed geometry exhibits increased tortuosity, which positively influences sound absorption. Furthermore, the continuous serpentine print paths make this geometry especially suitable for 3D printing with clay. To achieve structural stability, we defined multiple origins serving as starting points for the growth pattern. Replication may proceed from the inside outward or from the outside inward.

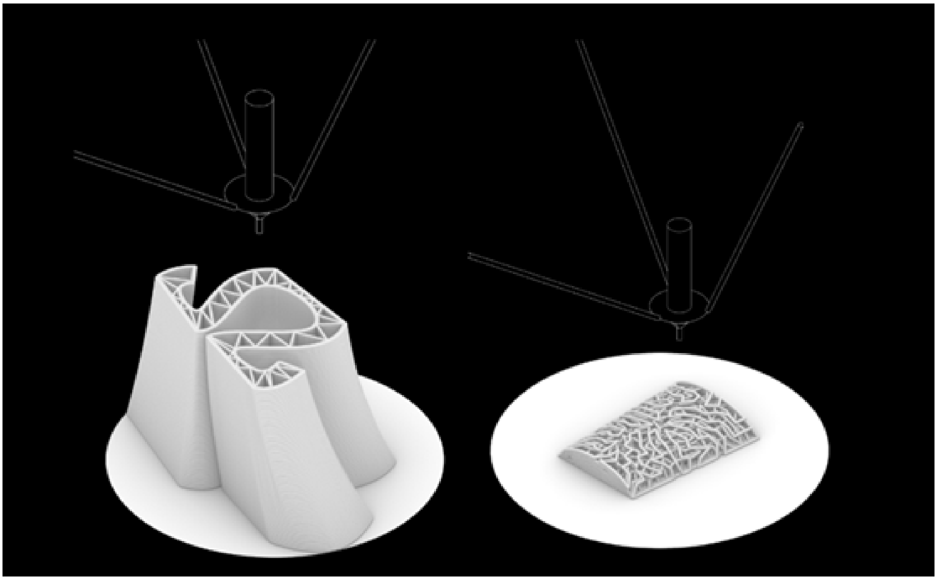

Fig. 7: Horizontal printing of the main structure and the growth pattern

2. Slicing

For generating the print paths and G-CODE, a slicer specifically developed for 3D clay printing at the Digital Design Unit (DDU) at TU Darmstadt was used. While most slicing software originates from the fused filament fabrication domain, optimized for 3D printing with thermoplastics, this slicer expands the range of clay-specific possibilities. Among its features are custom curve injections, which allows user-defined curves to bypass the slicing step and act directly as toolpaths, and non-planar slicing via gradient interpolation over tube-like mesh surfaces, robust even with self-intersecting meshes (e.g. for interior wall structures). The slicer is intended as an open framework for experimenting with alternative path generation strategies in research and teaching [12].

3. Printing

The demonstrator was fabricated in two steps: The main structure and the growth pattern were fabricated separately since the 3D clay printer (WASP 40100) lacked the range of motion and nozzle control required to reproduce the designed geometry in its full complexity.The main structure was printed in classical horizontal layers. Since the printer nozzle could only be adjusted vertically, the pattern had to be printed in a 90° rotated orientation. Due to the curved geometry, non-planar slicing was necessary to accurately generate the printing paths. The experimental slicer enabled the implementation of this non-planar printing strategy.

4. Connecting with slip

After a seven-day drying period, the parts were assembled by slip joining. Slip, a mixture of clay slurry and water serves as a glue that maintains the mono-material structure.

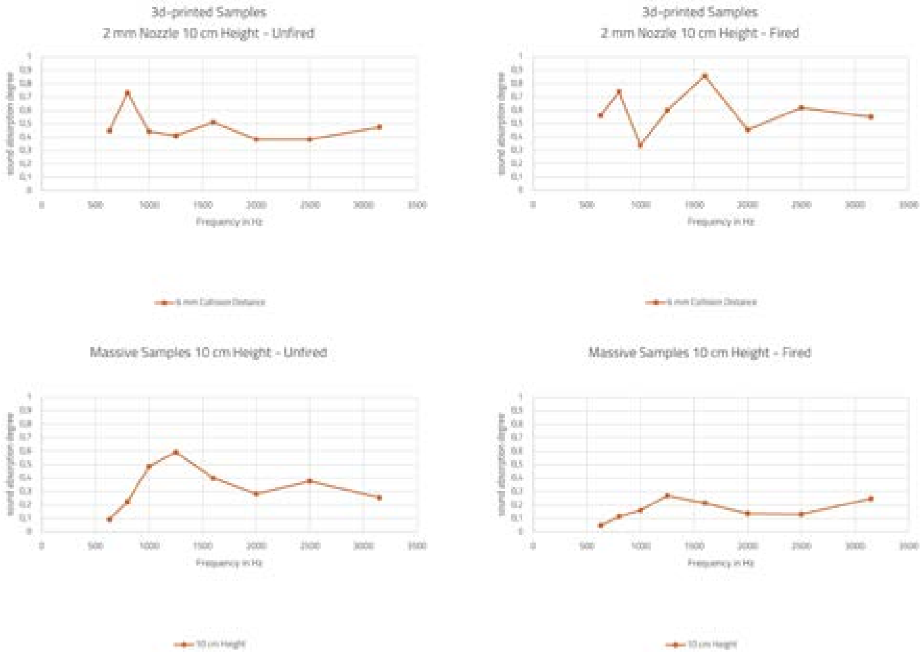

Fig. 8: Impedance tube measurement results

Measurement

In order to quantify the acoustic performance, the prototype was measured in a reverberation room followed by several small-scale samples. The absorption measurements of solid clay specimens confirmed the low values previously reported for rammed earth [6]. Unfired clay showed higher absorption than fired clay, which can be attributed to the sintering-related reduction of open porosity. In contrast, the 3D-printed, structured samples demonstrated a significant improvement in acoustic performance (Figure 8). As expected, specimen depth proved to be a key factor: 10 cm structures reached nearly twice the absorption of 5 cm ones, confirming the influence of layer thickness. Nozzle size also played a role: samples printed with a 2 mm nozzle consistently achieved higher absorption due to finer structures than those printed with a 4 mm nozzle, though even the coarser samples reached values of up to 80%. The highest absorption–around 86% at 1600 Hz–was measured for a fired sample with 10 cm depth, printed with a 2 mm nozzle and a collision distance of 6 mm. On average, fired structured specimens outperformed unfired ones, confirming that geometry can significantly enhance absorption even with acoustically rigid clay.

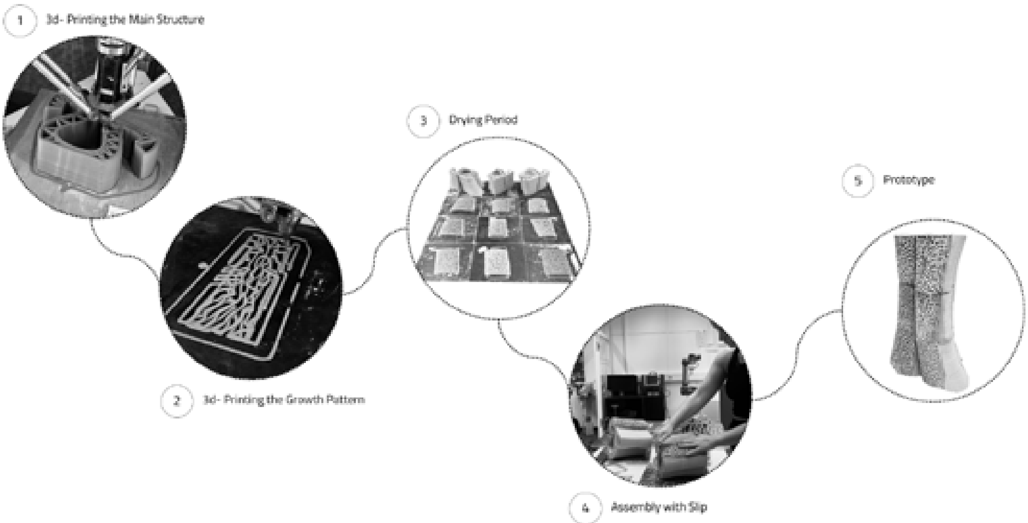

Fig. 9: Production & Assembly of the Prototype

Conclusion

This study introduces a process chain for 3D-printed clay absorbers, extending wall structures with acoustically effective layers that are both material-efficient and structurally stable. The prototype demonstrates how resonance-based cavities and porous growth patterns can create a recyclable, self-standing alternative to conventional acoustic foams using only ceramic material. While slip joining was applied in this study, future development may benefit from robotic fabrication. Overall, it shows how additive manufacturing, material research, and acoustic design can be integrated to advance sustainable building practices.

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Fig. 1: CoWave Neurodesign

FROM BRAINWAVE REACTIONS TO ADDITIVE MANUFACTURING: COWAVE'S NEURODESIGN SOFTWARE FOR HYPER-PERSONALISED DESIGN

AGA BLONSKA

AGA BLONSKA STUDIO

In today's rapidly evolving world, design is no longer defined solely by form and function. It has become a critical arena for addressing sustainability, personalisation, and human well-being. At the intersection of these challenges lies CoWave, a project that reimagines design as a direct translation of human emotion into material form. The project explores a trajectory that spans from the global need for sustainable practices, through the science of emotional resonance, to a novel neurodesign methodology linking brainwave activity to additive manufacturing.

The design industry contributes substantially to waste and overproduction. Many products are created for short-term trends or profit efficiency rather than longevity, reinforcing a culture of disposability. Furniture, acoustic panels, interior elements, and even architectural components are often discarded long before the end of their functional lifespan. The underlying cause is a lack of emotional connection between users and objects. To reduce waste, both production methods and the motivations behind keeping or discarding objects must be reconsidered.

Fig. 2: Electroencephalography (EEG) technology

Fig. 3: CoWave acoustic panel, wood dust

Mass production is unable to satisfy the increasing demand for individuality in the built environment. Contemporary users expect design to reflect personal identity as well as function. When objects and environments are created with individual resonance, they are more likely to be valued and preserved. Customisation thus extends the lifespan of products by making them emotionally relevant and personally meaningful.

Psychological research indicates that people tend to preserve objects and spaces that hold personal meaning rather than material or monetary value. Items without emotional attachment are easily discarded, while those that evoke memories or emotions are kept. In architecture and product design, this insight is fundamental: emotional connection becomes a hidden driver of sustainability. A chair, panel, or building that resonates emotionally with its user is less likely to be replaced or thrown away.

The emerging field of neurodesign addresses this connection by integrating neuroscientific understanding into creative processes. It proposes that design should be informed by human perception and cognition rather than dictated by external aesthetics or market trends. By grounding design in neurocognitive responses, neurodesign seeks to create objects and spaces that foster emotional resonance, promote well-being, and encourage preservation over disposal. Electroencephalography (EEG) technology provides a means to capture human perception in measurable form. EEG scanners record electrical brain activity in response to visual or sensory stimuli, allowing the identification of positive or adverse reactions to shapes, colours, and textures. In design contexts, this data translates subjective emotional responses into quantifiable input. EEG thereby enables a direct link between human emotion and design decision-making. Building upon this methodology, CoWave introduces a software platform that bridges EEG data and AI-driven design generation.The system records brainwave responses as users interact with visual stimuli, translating positive reactions into prompts for generative algorithms. The resulting three-dimensional forms are shaped by the user's own emotional responses. Each design thus becomes hyper-personalised, carrying an individual emotional imprint that enhances meaning and attachment. In a context defined by overproduction and environmental degradation, hyper-customisable design represents a promising alternative. By dedicating the design process to a single individual, CoWave increases

Fig. 4: CoWave haptics

the likelihood that the resulting artefact will be preserved and valued. Objects shaped by personal cognitive and emotional input are far less likely to be treated as disposable. Such an approach shifts design from trend-driven consumption to enduring ownership.

The CoWave system has been tested through a series of exhibitions that demonstrated its practical potential. Bespoke acoustic panels were generated from individual EEG reactions and 3D-printed using recycled materials. These artefacts embody the principle of design through emotion: each panel is unique, deeply personal, and inseparable from the emotional data that shaped it. The resulting works illustrate how intangible human reactions can be transformed into tangible, sustainable design outcomes.

Sustainability and circularity are central to CoWave's material strategy. The acoustic panels are produced from recycled plastics, wood dust, and coffee waste. Each unit weighs approximately 20 kg and can be returned, shredded, and reprinted, ensuring a closed-loop lifecycle. Additive manufacturing enables this process while minimising material waste, energy consumption, and water use compared to conventional production. Additive manufacturing (AM) provides the ideal technological basis for hyper-personalised design. Unlike traditional manufacturing, which depends on moulds and mass production, AM allows the creation of complex geometries with high precision and minimal waste. This flexibility supports individualised production without increasing cost or environmental impact. By merging EEG-based neurodesign with AM, CoWave demonstrates how emerging technologies can converge to produce sustainable, bespoke solutions for acoustic and architectural applications.

CoWave represents a new paradigm in design practice – one that unites emotional intelligence with environmental responsibility. Through the integration of EEG data, artificial intelligence, and additive manufacturing, the project demonstrates how emotionally resonant objects can extend product lifespans and reduce waste. This approach suggests a shift toward a form of sustainability that emerges naturally from attachment and care. When design responds to human emotion, preservation follows; neurodesign offers a path to achieve this connection at scale.

Fig. 5: CoWave acoustic panels

Fig. 1:
Vertico
3D concrete printing

FROM VISION TO PRACTICE: BRIDGING THE GAP IN 3D CONCRETE PRINTING

VOLKER RUITINGA
VERTICO

Abstract

Additive manufacturing has evolved from a research-driven vision into a practice-oriented industry, and one of the fastest-moving branches within the field is 3D concrete printing (3DCP). Vertico, a company dedicated to designing and manufacturing concrete 3D printing robots, demonstrates how this technology is being applied in practice today, what challenges exist in transitioning from academic environments to the construction site, and how the future of the field is being shaped through real-world projects.

The Landscape of 3D Concrete Printing

Within the 3DCP industry, two core technologies have emerged: one-component (1K) and two-component (2K) concrete printing. In the 1K system, dry mortar mix is combined with water before pumping and printing. The setting is controlled by an accelerant within the powder or by the material properties themselves. This approach is popular in large-scale housing or monolithic structures due to its simplicity. In contrast, 2K printing separates the accelerator from the base mix. The setting agent is injected only at the printhead, giving the operator real-time control over the setting process.This method is cleaner, more adaptable, and allows for precise printing, particularly when working with fine, architectural designs. Moreover, since the base mix remains fluid until it reaches the printhead, it can be pumped longer distances with lower pressure, enabling new configurations and on-site flexibility. While 1K is traditionally aligned with construction-scale applications like walls and houses, 2K opens doors to highly detailed architectural elements, high-resolution formwork, and hybrid systems. At Vertico, we focus primarily on 2K printing because we believe it offers the most promising future in terms of design freedom, control, and integration with structural systems. That said, 2K printing is increasingly being adopted for building-scale projects too.

Fig. 2: Vertico 1K Printhead

Fig. 3: Sirolis 3D Printing with Vertico technology ©Georgios

Fig. 4: Vertico 2K Printhead

Fig. 5: Printed concrete columns

From Research to Reality

At Vertico, our journey began with a deep commitment to exploration. We are not only machine suppliers but also active users. This dual role allows us to test the boundaries of what our machines can do while developing the features needed by clients in the field. In the past seven years, we've transformed experimental prototypes into robust, off-the-shelf technologies that are now installed in over x locations worldwide.

This growing network is forming a true ecosystem. We envision a future where a playground, bench series or art installation can be simultaneously printed by clients across different continents. In some cases, this is already happening. With installations in Europe, the Middle East, Asia, Australia, and the Americas, our goal is to enable distributed production through shared standards and robust technology.

Challenges Along the Way

Despite these advances, moving from research into real-world practice presents significant challenges. One of the biggest is demand. While the technology is ready, the market is still catching up. Architects and designers are interested, but general contractors and municipalities often hesitate to adopt new technologies without clear references or certifications. To address this, we focus our efforts on a few key product families:

- Planters and landscape elements: These are high-visibility, low-risk products that show off the design capabilities of 3D printing.
- Columns and structural formwork: These demonstrate hybrid methods where printed stay-in-place formwork is filled with reinforced concrete.
- Benches and public furniture: Functional and aesthetic objects that help bridge the gap between design and construction.
- Facades: These are beginning to attract interest from architectural firms interested in lightweight or textured surfaces.

By excelling in these areas, we aim to create anchor products that demonstrate quality, feasibility, and return on investment.

Fig. 6-11:
Vertico multiple products

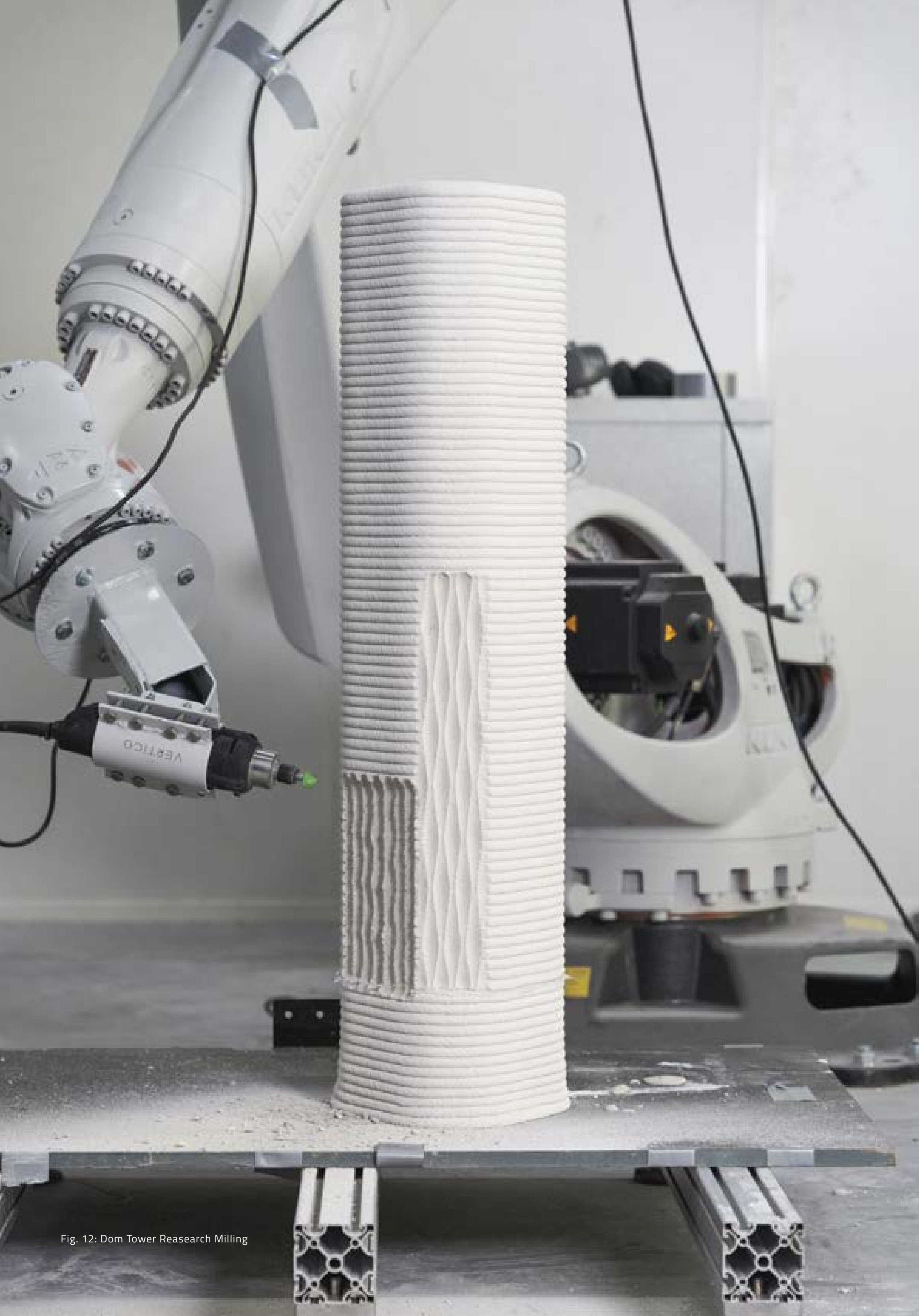

Fig. 12: Dom Tower Reasearch Milling

Material Supply and Global Readiness

Another persistent challenge is material supply. Many of the world's largest building material suppliers have been instrumental in kickstarting the 3DCP revolution. Their early enthusiasm allowed startups like ours to prototype and test. But now, the market needs to evolve from supplier push to user pull.

We need global supply chains that can deliver consistent quality across regions. That includes printable mortars, pigments, additives, and testing regimes. In Europe, we benefit from strong partnerships and technical support, but in other markets, supply can still be inconsistent. At the same time, sustainable and low-carbon concrete mixes are becoming more important. More clients now request cement-free formulations, or aggregates with high recycled content. The pressure to decarbonize is real, and the 3DCP industry is responding.

From Academia to Application

On the question of moving from academia to practice, one of the most promising developments we see today is the rising interest from applied research institutions. More and more universities, technical labs, and even semi-commercial or semi-governmental organizations are acquiring our machines, not only for academic study but also for prototyping real-world applications. This is a very positive trend, as it means that well-researched, documented product categories are being developed by research institutes in close collaboration with local partners who are eager to explore the potential of 3D concrete printing technology. These projects move beyond theory, producing practical outcomes that demonstrate how the technology can be applied in practice. Of course, as with any manufacturing process, there are still challenges to overcome, but this growing ecosystem of applied research provides valuable insights and momentum. Importantly, it also lays the groundwork for future standards and helps guide private-sector innovation. As machines become more affordable and user-friendly, the bridge between research and practice will only continue to shorten.

Vertico Research Directions: Color, Clay, Geopolymer, and Milling

From a research perspective, our current work focuses on several parallel directions. We continue to refine concrete printing technology by adding new features such as integrated color and improved start-stop control.

In addition, we have developed the ability to print clay with our machines, opening up possibilities for more bio-based approaches.

Together with a large consortium, we are also carrying out extensive research on geopolymer printing, aiming to reduce the environmental impact of concrete.

Another important line of work is milling: by combining 3D concrete printing with robotic milling, we can achieve fine surface finishes and highly detailed applications that go beyond the limits of extrusion alone.

Building the Future, One Step at a Time

Our focus has always been on achieving both high quality and lower environmental impact. By applying 3D concrete printing first to objects in open spaces - such as planters, urban design elements, and public installations - we create valuable, real-world results while refining the technology. From there, we expand into more complex applications like columns and facades, and eventually entire buildings. This step-by-step approach allows us to master the details, deliver excellence early, and build a strong foundation for the broader adoption of 3D concrete printing in architecture and construction.

Fig. 13: Dom Tower Research Milling

Fig. 1: Close-Up of a lattice structure as an insulating element, produced by paste extrusion from Magaverde biofiber

3D PRINTING OF INSULATION ELEMENTS FROM BIOGENIC FIBER RESIDUES

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Abstract

This research presents the development of Magaverde biofiber as a novel, biogenic 3D printing material for the Architecture, Engineering, and Construction (AEC) sector. Derived from digestate residues of biogas plants, the material integrates renewable energy production with sustainable building material innovation. A paste-like, fully compostable composite was formulated to enable extrusion-based additive manufacturing of customized insulation and structural components. The biofiber paste exhibits favorable rheological properties, including pronounced shear-thinning behavior, allowing precise deposition and rapid hardening without collapse. Adaptations of existing clay 3D printing systems enabled the production of large-scale, form-independent elements with adjustable density and low thermal conductivity. The resulting components demonstrate mechanical performance, processability, and surface qualities suitable for architectural applications such as thermal and acoustic insulation panels. The project exemplifies a circular, climate-positive approach to material development, advancing sustainable additive manufacturing within the AEC industry.

Motivation and background - What is biofiber?

In its New European Bauhaus (NEB) initiative, the European Commission is calling for a rethinking of the use of existing building materials and demanding the introduction of new, sustainable alternatives for the AEC sector [3]. At the same time, the European Union has set ambitious climate protection targets and committed itself to taking measures to obtain at least 42.5% of its gross energy consumption from renewable sources by 2030 [2]. The project presented here investigates a strategy for not only making AEC building materials more environmentally friendly, but also combining their extraction directly with the growing demand for sustainable energy production, thereby addressing both issues at the same time.

A key element in this context is the use of biogas plants, which produce biomethane capable of substituting fossil natural gas [1]. Current developments reveal an ongoing trend in the commissioning of biogas plants, the quantities of biomass processed, and the total energy generated in the form of electricity and gas [5]. In Germany alone, the amount of biomethane fed into the natural gas grid has almost doubled over the past decade [1].

Biogas plants primarily process energy crop silages and livestock manure as feedstock. In particular, silages are produced in increasing quantities, partly due to the rising production of other renewable energy carriers such as biodiesel. The conversion of biomass takes place via anaerobic digestion, during which the organic material is microbially degraded, generating methane. This methane can either be combusted on site in combined heat and power (CHP) units and fed into a district heating network, or it can be processed and injected into the public natural gas grid [5]. During the digestion process, digestate remains as a by-product of the biomass that is not fully degraded. Digestate consists mainly of a nitrogen-rich liquid fraction with a dry matter content of around 7%, composed largely of indigestible cellulose and lignocellulose fibres [8]. While the liquid fraction is widely used as a high-quality biofertilizer and serves as a valuable substitute for mineral fertilizers, the fibre-rich fraction is still largely regarded as a residual product. It is either composted at significant cost or spread on agricultural land together with the liquid fraction as a carrier material. A schematic representation of the material flow in biogas plants is shown in Figure 2.

Given the anticipated continued expansion of biogas production and the corresponding increase in biomass processing, the amount of fibre-rich digestate is also expected to grow. This underscores the need to develop new valorisation and processing strategies for these underutilised biofibre residues in order to fully exploit the ecological and economic potential of biogas production.

Under the brand name Magaverde, the Gesellschaft für Nachhaltige Stoffnutzung mbH (GNS) and BENAS Biogasanlage GmbH, has been engaged since 2008 in the recovery, processing, further refinement, and utilisation of biofibre residues from biogas plants. In 2016, the first large-scale industrial facility for the production of Magaverde biofibre was commissioned.

The recovered biofibre can be successfully processed into paper and cardboard [7] and is also suitable for moulded fibre applications, enabling the creation of sustainable packaging solutions. A life-cycle assessment conducted by the Institut für ökologische Wirtschaftsforschung (IÖW) demonstrated that the production of such paper-like products from Magaverde biofibre results in a significant reduction in water consumption and greenhouse gas emissions compared to conventional products made from wood fibre [2]. The environmental benefits are even more pronounced when Magaverde products replace plastic-based packaging materials. Furthermore, Magaverde cardboard products are fully compostable, ensuring their reintegration into natural material cycles.

In collaborative projects with the Institute of Printing Science and Technology (IDD) at Technical University Darmstadt, research has also demonstrated the printability and finishing properties of Magaverde paper, thereby enabling value-added packaging applications for consumer goods [6]. These developments facilitate the production of a highly sustainable yet high-quality packaging material, offering a viable alternative to conventional paper and plastic solutions.

Building on the promising results and high processability of Magaverde biofiber demonstrated in previous projects, the current research initiative aims to further develop this material into a pasty mass suitable for clay-based 3D printing applications. This advancement seeks to expand the sustainable material's range of use beyond paper and cardboard substitutes, enabling its application in the creation of functional,

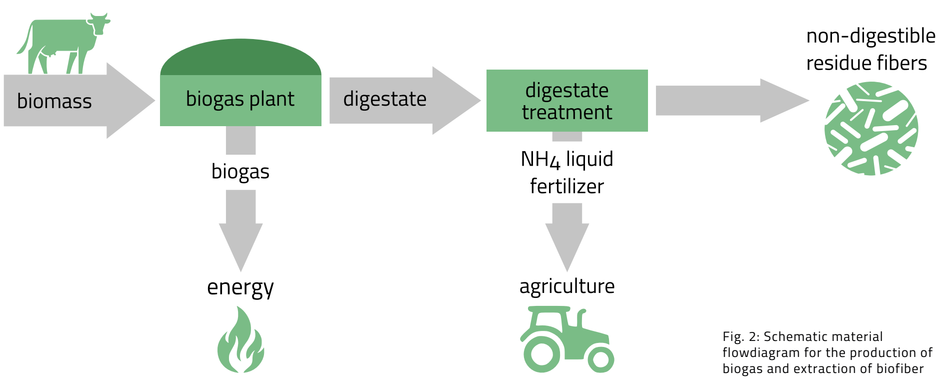

Fig. 2: Schematic material flowdiagram for the production of biogas and extraction of biofiber

Fig. 3: Cured samples of the 3D biopaste (middle) and base raw materials

three-dimensional objects. The primary goal is to employ the material in the production of customized insulation elements for both thermal and acoustic purposes. Unlike conventional panel-based materials that result in significant cutting waste, these components can be fabricated as unique, form-independent pieces directly through additive manufacturing.

Magaverde biofiber as a 3D build material

Numerous requirements were placed on the novel material mixture of a 3D printing material based on Magaverde biofibers made from biogas production residues. A key requirement was to develop a matrix material (binder) for the fibers that, like Magaverde biofibers, is renewable and sustainably produced, as well as fully compostable. At the same time, the technical requirements of 3D printing had to be met as best as possible. The printing paste must be sufficiently low in viscosity for extrusion, but must not collapse during printing and must harden quickly. Other requirements for use as a construction element included high water resistance, low thermal conductivity, adjustable density, and fire protection specifications.

To solve these challenges, the suitability of natural polymers and polymerizable native substance groups was investigated. Chemically modified materials were not used, as these can negatively affect biodegradability. As a result of numerous laboratory tests and systematic series of experiments, a multi-component matrix of hydrophilic and hydrophobic biogenic materials was developed into which the Magaverde biofibers can be easily incorporated and bonded intimately despite adhering moisture. By adding minerals with binding properties and small additions of catalytically active minerals, the viscosity of the biogenic printing paste, as well as its subsequent drying and curing, was increasingly optimized (Fig. 3).

In addition, the rheological behavior of the newly developed paste was examined in detail. Thanks to its composition, the material shows a distinct shear-thinning character - becoming more fluid under pressure during printing and regaining firmness after deposition. It was also shown that a reduction in thermal conductivity and density can be achieved through recipe variations. To further enhance performance, various slow-acting natural blowing agents were tested. These expand during curing, creating a light, porous structure that reduces density and weight while improving the thermal insulation properties of the printed elements. In line with the project's sustainability goals, biocarbon is currently being explored as a natural flame retardant. Beyond its flame retardant effect, biocarbon contributes to a net CO_2-negative material balance therefore turning ecological responsibility into a tangible design advantage.

The Magaverde biofibers from the digestate treatment are odorless due to the previous cleaning process, with the adhering nutrients being recovered as mineral fertilizers. The fiber length and width are adjusted using a wet refiner commonly used in paper production. For this purpose, different fiber lengths of a fiber batch were tested in several test series. Approximately 54% of the fibers were between 200 µm and 1 mm, which proved to be the optimal fiber fraction (Fig. 4). However, the oversize consisted of a high proportion of agglomerated fibers, so the proportion of usable fibers can likely be increased to 80-90% through adapting the technology. Alternatively, dry milling is also possible.

Additive Manufacturing of Magaverde biofiber

For more than four years, Additivum GmbH has been engaged in the development and operation of 3D printing systems for the processing of clay and the additive manufacturing of ceramic products such as tableware, vases, and urns. To this end, a printing system has been designed that enables the reliable and uniform additive processing of the highly viscous and abrasive clay material. In addition, both upstream process steps for material preparation and feeding, as well as downstream steps for drying, finishing, and firing, have been established. This integrated production chain allows the company to economically manufacture products ranging from one-off items to large-scale series.

Within the framework of the joint project, Additivum is responsible for ensuring the additive processability of Magaverde biofiber paste for the production of customized, large-volume components. For this purpose, the existing ceramic 3D printing process is being adapted to the specific characteristics of the biofiber paste. In particular, the process is being modified to accommodate the fibrous and partially adhesive mass, which is being tailored to the developed 3D printing system in collaboration with GNS.

A well-known hurdle in processing pastes in 3D printing, such as clay, is the collapse of the unfinished component during printing due to its own weight. This often limits the maximum build height or maximum build volume of the components that can be produced.

Fig. 4: Fractions of a refined Magaverde biofiber sample

Fig. 5: Twin-screw extruder setup during testing of blending of two dyed pastes (blue and red)

Fig. 6: Adapted clay 3D printing system during the fabrication of a honeycomb demonstrator made from Magaverde biofiber paste.

To address this problem and produce larger components from biofiber paste, an experimental print head with a twin-screw extruder (Fig. 5) was designed in cooperation with IDD, which conveys the fibrous material and enables targeted blending of fibers, binders and hardeners as well as catalysts in situ, i.e. just before the material is deposited. This just-in-time blending enables the processing of a highly reactive paste that starts to cross-link shortly after its deposition initiating its hardening process. This makes it possible to print larger, more voluminous parts, as otherwise the part would begin to flow and destabilize due to its own weight pushing on the uncured and therefore soft structure. In addition, the entire material feed system of the clay printer has been optimized to withstand high pressures of up to 20 bar and thus be able to process even higher viscosity materials than before. This allows the use of the firmest possible base paste material with a higher solid content, which is beneficial for structural stability during printing as well as for the material strength of the final product. This also reduces the amount of binder required. In the future, there are plans to cascade the material cartridges in bundles, enabling cartridges to be changed during printing without any loss of pressure, enabling larger objects to be created without any visible material transition points.

At the same time, research is also being conducted into continuous material feeding. The interplay between material composition, material processing, printing parameters, and the design of the 3D printing system (especially the print head and material feed) is constantly being improved through simple benchmark tests, with the focus on material feedability and build stability. The printed objects made of biofiber cure completely at room temperature. However, it has also been shown that the curing process can be shortened by a factor of 10 through controlled heat treatment. Controlled heating of the components also allows the cross-linking of the binder to be influenced, which means that the material properties of the final product can be adjusted to a certain extent. We expected that the strength of the components can be further increased by an annealing step. The existing production line at Additivum comprises clay printers, featuring a build volume of approximately 500 mm × 400 mm × 400 mm. This configuration was designed to meet the requirements of previous ceramic manufacturing processes and has proven sufficient to date. All prior benchmark experiments using biofiber paste have also been conducted on these systems (Fig. 6). However, the production of insulation components for the construction industry demands a significantly larger build volume.

Fig. 7: Large scale cartesian clay 3D printer witha build volume of approximately 1500 mm x 1500 mm x 2000 mm

Fig. 8: Fully cured sample cylinders made to investigate the critical build height before failure under own weight

To address this need, a new cartesian 3D printer with a build space of 1500 mm × 1500 mm × 2000 mm is currently built (Fig. 7). This configuration offers a build volume more than fifty times greater than that of the existing setup.The design focus for this large-scale printing system lies primarily on achieving high structural rigidity, which is essential due to the considerable moving masses involved in processing viscous materials such as clay or biofiber paste. Maximizing printing speed is therefore of secondary importance and usually counterproductive when processing pastes. To ensure precise positioning and mechanical stability, the printer employs ball screw drives on all three coordinate axes, allowing the print head to move with both high accuracy and sufficient stiffness.

The mechanical design of the system follows a gantry architecture, featuring a movable portal. This enables the entire printer to traverse across the build surface, i.e., the build platform. Such an approach provides a decisive advantage: printed components that remain in a soft, deformable state during curing do not need to be moved immediately after printing. Instead of removing the fragile part from the printing area, where deformation or damage could occur, the printer itself is moved away from the platform, thereby preserving the integrity of the printed structure.

The print head suspension has been designed with a modular architecture to ensure future adaptability. This allows for the integration of new print heads as required for the processing of additional material systems. In the long term, this modular concept enables the use of a broader range of pastes, potentially requiring the incorporation of additional feeding or mixing components within the print head. As such, the developed system represents a flexible and scalable platform for large-format additive manufacturing applications.

Results and conclusion

In all benchmark tests conducted so far, the Magaverde biofiber paste has shown processing characteristics very similar to clay within the 3D printing process. Following the approach of Tripathi et al. [9], hollow cylindrical test specimens were designed and produced to investigate the critical build height before failure under the material's own weight (Fig. 8).

These experiments enabled the optimization of material and printing parameters and successfully demonstrated the feasibility of producing larger components using the described process.

The preparation of the material, cartridge filling, and cleaning procedures were found to be comparable in effort to those required for clay. An initial stickiness of the paste was largely mitigated by increasing the fiber content, adding finely ground fibrous powder, and allowing for a longer swelling period after preparation. These adjustments significantly reduced the cleaning effort after processing.

The printed components cure completely at room temperature and exhibit weight, texture, and appearance closely resembling wood. They can also be sanded, painted, or otherwise finished using typical woodworking techniques. The resulting parts are strong and rigid, allowing for conventional mechanical anchoring and load transfer, making them suitable for a wide range of applications as insulation panels.

Beyond their intended use as thermal and acoustic insulation panels, the material also shows potential for other wood-replacement applications. In the future, paste-based 3D printing with Magaverde biofiber could enable the production of furniture, cladding, and facade elements for both interior and exterior use.

Acknowledgements

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Fig. 1: Wavehouse Facade, ©SSV Architekten

FROM PROTOTYPE TO STRUCTURE

Large-Format 3D Printing Directly on the Construction Site – Wavehouse Heidelberg

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SSV ARCHITEKTEN HEIDELBERG

Abstract

The Wavehouse represents Europe's largest building constructed entirely on-site using 3D concrete printing. Located within the redevelopment area of the former Campbell Barracks in Heidelberg, the project explores the architectural, technological and ecological potentials of additive manufacturing under real construction conditions. Conceived as a data center, the Wavehouse combines a parametric design strategy with a fully digital fabrication workflow, achieving material efficiency, structural precision and formal expressiveness. The project provides key insights for the future integration of large-scale 3D printing into sustainable building practice and urban transformation contexts.

Context and Motivation

The transformation of the former Campbell Barracks – built in 1938 and later used as NATO Headquarters – into a civilian urban district exemplifies the adaptive reuse of post-military sites in Europe. The overarching design strategy for the area merges listed heritage structures with selective contemporary interventions.

Within this framework, the Wavehouse establishes a benchmark in digital construction. As Europe's largest fully 3D-printed building, it embodies both the technological innovation of on-site additive manufacturing and the cultural shift toward resource-conscious, digitally integrated building processes.

Project Genesis and Collaboration Framework

The initiative originated from the client's interest in emerging 3D printing applications and their potential for architectural implementation.

SSV Architekten, with prior experience in 3D printing for physical modelling, led the conceptual and design development. The interdisciplinary project consortium comprised partners for structural design (Mense + Korte), 3D printing execution (Peri 3D Constructions GmbH) , and material innovation (Heidelberg Materials).

The chosen building typology – a server facility – offered a controlled environment to test structural, climatic, and process-related parameters under realistic constraints.

Fig. 2: Wavehouse, ©Adrian Schulz

Design Strategy and Digital Workflow

The architectural concept investigates the interface between computational design and robotic construction. The façade geometry, inspired by wave-like motion, articulates the building's dynamic expression and gave rise to its name.

Visible printing layers were deliberately retained to manifest the logic of fabrication. Parametric modelling enabled the calibration of geometrical tolerances, such as maximum overhang angles, directly within the design model. The digital model was seamlessly transferred to the printer control environment, resulting in a continuous digital-to-physical workflow from design to production. The outcome is a functional yet sculptural building that demonstrates the spatial precision and aesthetic potential of additive fabrication.

Construction Process and Technical Parameters

The Wavehouse was produced entirely without formwork, except for the prefabricated ceiling components. Two 6 cm thick concrete shells were printed in 1 m-high layers and subsequently infilled with in-situ concrete. To ensure process stability and uniform curing, the structure was divided into three horizontally sequenced segments, printed successively and mechanically joined.

The building measures 54 m in length, 11 m in width, and 9 m in height. Printing time totalled 170 hours, consuming 333 tons of mineral-based printable concrete. During fabrication, environmental factors such as strong solar radiation and wind affected hydration, leading to localized cracking – valuable feedback for process optimization and material calibration in future projects.

Fig. 3: Printing Process Wavehouse, ©SSV Architekten

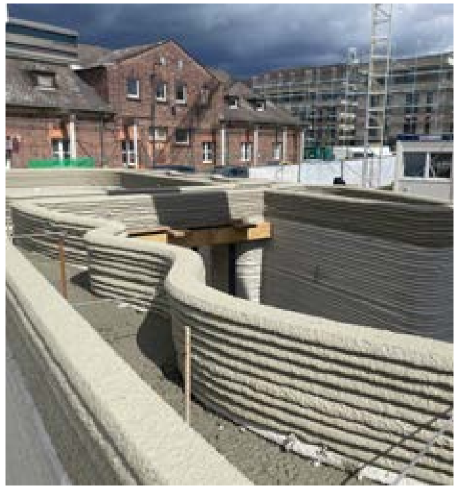
 

Fig. 4: Printing Process Wavehouse, ©SSV Architekten

Material System, Sustainability, and Energy Performance

The structure employs a fully recyclable mineral concrete, processed without reinforcement, enabling slender cross-sections and a minimized material footprint. The green façade contributes to urban microclimate regulation and contextual integration.

Operationally, the building operates without a heating system: internal server heat covers the entire heating demand, with cooling required only during summer peaks. Excess heat is transferred via pre-installed conduits to neighboring buildings for reuse.

The project embodies sufficiency and circularity as guiding principles. 3D printing applies material only where structurally necessary, eliminating waste and enabling reuse of components. The flexible interior layout ensures long-term adaptability for future reprogramming.

Evaluation of On-Site 3D Printing

Empirical data from the Wavehouse demonstrate several advantages of large-scale additive manufacturing:

(1) Design Freedom: Complex, sculptural forms can be realized without conventional formwork
(2) Labor Efficiency: Reduced on-site workforce mitigates the impact of skilled labor shortages and enables process automation
(3) Productivity: Significantly accelerated construction times under controlled conditions
(4) Ecological Efficiency: Full recyclability, reduced embodied carbon through slender geometries, and zero waste
(5) Economic Feasibility: Comparable costs for bespoke structures; optimization potential for standardized applications remains under development.
Current limitations are primarily regulatory (safety, certification) and logistical (transport, weather dependency)

Fig. 5: Follow-Up Research. The „Dreihaus" Prototype, ©PERI3DConstruction

Follow-Up Research: The "Dreihaus" Prototype

The subsequent project Dreihaus, currently under construction in Heidelberg, integrates the insights from the Wavehouse to test the scalability of 3D printing for serial housing. Process optimization enables continuous multi-storey printing without idle days. The adaptable floor plan allows typological variation and rapid customization.

Technical refinements include:

(1) Flap elements that align wall geometry and facilitate subsequent construction works
(2) First-time integration of a load-bearing printed wall with approval
(3) Elimination of lintels through full-height openings
(4) Local production of printable material in nearby Village Leimen
(5) Modular segmentation allowing adaptive printing sequences responsive to weather and workflow conditions

Discussion and Future Outlook

On-site 3D printing is unlikely to replace conventional construction in the near future but constitutes a vital complement within hybrid building systems. The method challenges existing codes and standards, necessitating adapted regulatory frameworks.

Parallel research focuses on alternative, low-carbon binders and geopolymer concretes to further reduce environmental impact. The integration of additive processes into modular and serial construction presents a promising pathway for industrialized yet individualized architecture.

The Wavehouse thus represents not only a technological achievement but also a paradigm for a new architectural culture – resource-efficient, digital, sculptural, and site-specific.

Its successor, the Dreihaus, aims to prove that additive construction can achieve, or even surpass, conventional methods in speed, cost efficiency, and sustainability.

Fig. 1: Wonova Facade Renovation, ©etcetera

ONE LAYER AT A TIME: FOUR VISIONS FOR A 3D-PRINTED FUTURE

ROB HENDERSON

ETCETERA

Abstract

We, at etcetera, have long been fascinated by the idea that buildings, homes, and even furniture could evolve beyond their traditional constraints. What if construction didn't require mountains of concrete, endless deliveries, or months of labor-intensive installation? What if a home could grow as its residents grew, or a façade could be printed on site, perfectly optimized for energy, structure, and sustainability? Over the past several years, we've pursued these questions through four projects that explore the potential of 3D printing and digital fabrication in architecture and design: Wonova, Grow, Auralith, and the Septa Chair. Each project tackles a different scale of design and social impact, but all share a common philosophy: design, technology, and sustainability are not mutually exclusive categories; they should combine to create objects, spaces, and systems that are smarter, greener, and more attuned to human needs. From large-scale façades to intimate chairs, from urban communities to remote landscapes, these experiments have helped us imagine a future where construction is circular, homes are dynamic, and design is deeply responsive to both people and place.

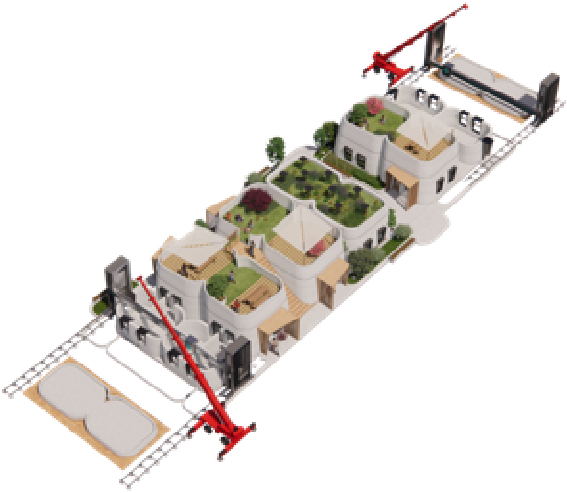
Wonova: printing the building envelope of the future

The construction industry is one of the largest contributors to global carbon emissions, and much of that impact is baked in before a single brick is laid. Conventional building envelopes are a patchwork of materials: panels, insulation, fasteners, sealants, and coatings, all sourced from different suppliers, transported in separate shipments, and installed by teams of workers using time-intensive methods. The result is inefficiency at every step—material waste, energy waste, and carbon-heavy logistics.

Our goal with Wonova was to rethink this entire process. Rather than improving incrementally on standard façades, we wanted to ask a radical question: what would a building envelope look like if it were designed from the ground up to be printed, recycled, and refabricated?

We started by embracing the concept of mono-materiality: using a single, recyclable material to fulfill multiple roles. Bio-based polyamide emerged as our material of choice, thanks to its structural performance, thermal efficiency, and high recyclability. In essence, it allows us to print a façade system that can do everything traditional façades do—but with far less waste and a much smaller carbon footprint.

On-site 3D printing is central to Wonova's approach. By producing the envelope where it will be installed, we eliminate the energy costs associated with transporting



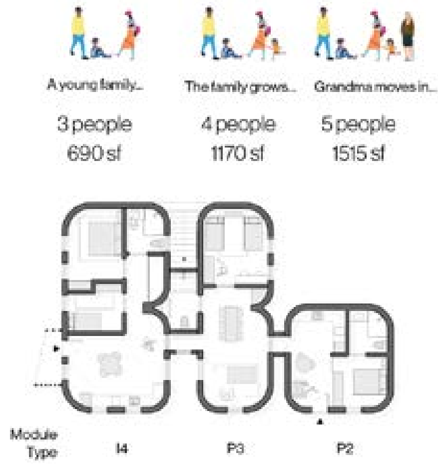


Fig. 2: Grow Progressive Housing, ©etcetera

bulky panels. Robots can already place anchors and install panels, and will soon print entire walls directly in place. This robotic integration is not science fiction—it's the near-future of construction, and we're building partnerships to bring it into reality.

Beyond materials and mechanics, Wonova is computationally optimized. With the help of our partners at EOC Engineers, the system has been studied digitally to maximize structural efficiency and thermal performance. This flexibility means façades can be tailored to specific climates, regulations, and even aesthetic desires. It's not just a façade; it's a system that adapts to context while reducing waste at every stage.

We envision a future where building envelopes are not disposable commodities but living, recyclable systems. Façades that can evolve, be repaired, or even reprinted entirely without contributing to landfill or carbon emissions. For us, Wonova is more than an experiment—it's a blueprint for what construction could be if we dared to rethink everything.

Grow: housing that evolves with you

While Wonova tackles the systemic inefficiencies of construction, Grow addresses a different challenge: how housing can be sustainable, affordable, and dynamic over a the lifetime of a family and community. Housing is usually static, bought or built as a fixed asset that rarely adapts to changing circumstances. But life isn't static, and neither are our needs.

Grow is built around the concept of progressive housing: the concept that a family can expand their home as their financial means evolve. We designed the system to start with a core structure, printed with concrete using a modular gantry-based 3D printing method. Adjustable bollards support the rails, allowing the infrastructure to be reused for expansions. Prefabricated concrete slabs integrate seamlessly with printed grade beams, and the modular system ensures maximum wall-sharing efficiency. Even areas of the site that aren't immediately built on are not wasted—they become plazas, gardens, or playgrounds, ready to transform when the time is right.

The social implications of Grow are as important as the technical ones. Residents are not passive occupants; they become active participants in shaping their environment. They can learn 3D printing techniques, contribute to expansions, and gain skills that have real-world value. Over time, this hands-on engagement fosters a sense of ownership and community, creating neighborhoods that are resilient, adaptive, and deeply connected.

Environmental sustainability is embedded into every aspect of Grow. Green roofs provide insulation and

Fig. 3: Grow Street View, ©etcetera

facilitate rainwater collection. Shaded courtyards act as natural air filters. Micro-wind turbines and photovoltaic foils harvest clean energy. Every element, from the placement of a garden bed to the routing of a plumbing chase, is designed to maximize efficiency and enhance well-being.

Financially, Grow creates access. Low-income families, immigrants, young couples, and retirees can enter a housing system that grows with them, turning aspiration into attainable reality. This progressive model is not just about buildings; it's about creating communities that evolve with life's rhythms, providing long-term stability and opportunity.

Grow demonstrates that 3D printing is not merely a tool for novelty–it can reshape the social, economic, and environmental dimensions of housing. It's architecture as a living system, responsive to people, place, and time.

Auralith: responsive architecture for remote and sensitive landscapes

If Grow is about social adaptability, Auralith is about ecological responsiveness. Designed in collaboration with Ergin Birinci Studio for a private client with a vision for sustainable, climate-aware living, Auralith combines digital fabrication with deep knowledge of local materials and environmental conditions. The goal was ambitious: a fully 3D-printed home using site-sourced materials, minimizing embodied carbon while achieving comfort, resilience, and beauty.

The home is composed of four zones–living, sleeping, service, and guest–arranged around a circular core, with courtyards at every scale. The heart of the house is an interior courtyard that serves as both visual anchor and natural ventilation engine. As one moves through the building, the sequence of open and shaded spaces creates a rhythm of discovery: intimate spaces for reflection, terraces cooled by water, and interstitial courtyards that mediate sunlight and airflow.

The innovative construction concept combines robotics with local material intelligence. Gypsum, limestone, and dolomite can be sourced at and around the site. It would be mixed with local river sand and water, then fused with polymer additives to produce a printable composite. Robots handle the 3D printing of walls and roof components, roof component installation, and material management, minimizing human labor while maximizing precision and speed. The site is touched only lightly. Container-based control centers, prefabrication zones, and minimal excavation preserve the landscape and reduce environmental impact.

Auralith is also digitally responsive. Screens track the

Fig. 4: Septa Chair, ©etcetera

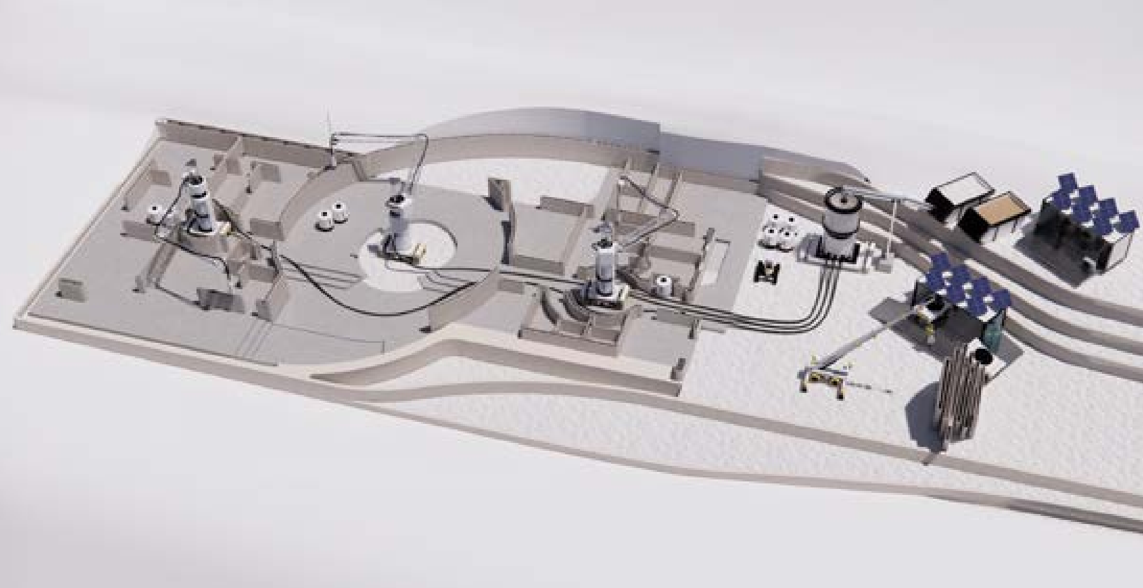


Fig. 5: Auralith Production, ©etcetera

movement of the sun and wind, adjusting throughout the day to optimize shading and airflow. Collected humidity irrigates green roofs and landscaping, while photovoltaics and energy-efficient heat pumps provide a measure of autonomy from the grid. In essence, the house listens to its environment, adapts to it, and integrates human and ecological needs into a single living system.

This project demonstrates that technology should extend the vocabulary of architecture, allowing buildings to harmonize with their surroundings rather than dominate them. Auralith is a model for future construction in remote or sensitive environments: scalable, adaptable, and deeply responsive to both climate and culture.

Septa Chair: design, comfort, and production in harmony

If Wonova, Grow, and Auralith reimagine architecture at the scale of buildings and communities, the Septa chair brings the philosophy home–literally to the scale of furniture.

The Septa chair is a rocking lounge chair designed to balance elegance, ergonomics, and technological sophistication. Its form is composed of a single surface that wraps around and through itself. In the parlance of 3D printing a digital model of that form is “sliced”. Those slices–creating a continuous loop–and associated form are used to guide the path of the robotic arm and the material deposition. Often, a processing software generates the most efficient “infill” to strengthen the connection of outer surfaces. But in this case, the infill is an integral part of the chair design, formed from the same continuous surface. The Septa chair is printed by a pattern of alternating layer types made of two alternating curve patterns that create the continuous material loop needed for the LFAM.

We collaborated with Differential on computational design and worked with Nagami on the robotic large-format additive manufacturing (LFAM) production. As a team, we developed the novel design, development, and production process described above that allows for the unique composition of the Septa chair. Each curve, each seam, is the result of algorithmic modeling calibrated to respond to human posture and comfort.

Septa demonstrates that even small objects benefit from the same principles guiding large-scale architecture: precision, adaptability, and harmony between human needs and material intelligence. In every rocking motion, it’s a reminder that the future of design is not simply about automation–it’s about enhancing experience, connecting technology and craftsmanship, and creating objects that are responsive, sustainable, and humane.

Fig. 5: Auralith Aerial, ©etcetera

Toward the printing of everything

Together, these four projects form a continuum of exploration, showing how 3D printing is reshaping everything from the envelope of a building to the chair we sit on. Each reflects a different dimension of possibility: Wonova challenges industrial inefficiency, Grow reinvents housing as a living system, Auralith integrates architecture with environment, and Septa Chair distills these principles into intimate, human-scale design.

Across these scales, several themes emerge. Circularity matters: materials should be reused, not wasted. Adaptability is essential: homes and communities must evolve with human needs. Integration with environment is no longer optional: architecture must listen to wind, sun, and topography. And technology, 3D printing in this case, is a tool, not a replacement, for thoughtful design–it enables us to imagine solutions that were impossible a generation ago.

We're not building for a single moment in time; we're building for decades, for generations, for systems that can grow, repair, and adapt. These projects are more than experiments–they are prototypes of a new design ethos: architecture that is alive, responsive, and deeply connected to the spaces and landscapes it inhabits and the people who use it.

The future we imagine is one where construction is no longer synonymous with waste, where housing evolves alongside its residents, where buildings respond to climate instead of exacerbating it, and where technology amplifies human creativity rather than replacing it. By rethinking scale, materials, and process, we are printing the foundations of a sustainable, adaptable, and visionary world.

It's a future built one layer at a time–and we are just beginning.

Fig. 1: Nagami x Ross Lovegrove - Ganic at CFuture Lab Schenchen

FROM WASTE TO LUXURY: HOW LUXURY BRANDS ARE ACTIVELY ADOPTING RECYCLED MATERIALS INTO RETAIL STORES

MANUEL JIMENEZ GARCIA
NAGAMI DESIGN

Introduction: Manufacturing as Cultural Act

At a time when the additive manufacturing industry is shifting from prototyping to full-scale production, design and architecture are emerging as powerful laboratories of innovation. Within this transformation, Nagami has become a reference – a company translating industrial intelligence into emotional experience, and redefining waste as the raw material of beauty. Founded in 2016 in Spain, Nagami operates 21 industrial robotic arms, making it the largest large-scale 3D printing platform in the global design and architecture sector. Its mission is to demonstrate that the same technologies used in aerospace or automotive can also produce objects that resonate culturally and sensorially. In other words: that manufacturing can be poetic – a form of cultural expression. The company's ethos is rooted in the belief that industrial production can serve society not only functionally but also emotionally – transforming material waste into cultural value.

From Research to Industry

Nagami's foundation stems from the research trajectory of Manuel Jiménez García, trained at the Architectural Association (AA-DRL) and former Associate Professor at The Bartlett School of Architecture, UCL, where he directed the Architectural Computation programme. His academic research in algorithmic design, robotic fabrication, and digital materiality explored how data and machine behaviour could shape new spatial and material logics. This work contributed to a broader dialogue on the integration of computation and fabrication in architectural practice.

Nagami emerged as the material continuation of this research – moving from robotic experiments and generative models into a fully operational industrial environment. The company was conceived as a bridge between the speculative, code-driven domain of academia and the pragmatic world of manufacturing, transforming theory into production and research into narrative. From its inception, Nagami played a fundamental role in – and was deliberately founded with the goal of – perfecting digital design research and translating it into a tangible market reality within design and architecture. This continuity between thinking and making forms the backbone of Nagami's identity. It also reflects a shift in the cultural status of fabrication: from the invisible background of industry to a visible, expressive component of design.

The Shift: From Waste to Beauty

Most additive manufacturing discussions focus on efficiency, precision, and cost reduction. Nagami's contribution lies elsewhere: in turning sustainability into desire. Its guiding principle – From Waste to Beauty – repositions the narrative of circular materials away from guilt and toward fascination. Sustainability becomes not a moral burden but a form of creative luxury, where

Fig.2: Nagami x Cloud9 - CaixaForum Valencia

innovation aligns with seduction. In Nagami's practice, post-industrial plastics, biowastes, and recycled composites are not limitations but the foundation of a new aesthetic vocabulary. The chromatic variations, surface micro-textures, and thermal gradients of recycled matter are embraced as expressive qualities rather than defects. Where traditional industry sought uniformity, Nagami finds nuance; where production once erased material character, Nagami amplifies it. This radical re-evaluation of industrial imperfection suggests a new aesthetic paradigm for the circular economy.

The resulting pieces are not mere "eco-objects," but artefacts that reveal the thermodynamic memory of their making. Each extrusion line and each modulation in gloss captures the flow of polymer, a visualisation of kinetic energy frozen in form. This approach transforms additive manufacturing into a form of digital craft – one that reclaims emotion and tactility within robotic precision, transforming machine behaviour into a form of creative authorship.

Large-Scale Robotic Printing as Expressive Medium

Nagami employs robotic additive manufacturing not only as a tool of production but as a design medium in its own right. The six-axis robot becomes a sculptural instrument capable of interpreting geometry, material,

and gesture simultaneously. The precision of the toolpath, the rhythm of layering, and the dynamics of extrusion pressure all contribute to the morphology of each object.

By treating extrusion parameters as design variables, Nagami has developed a vocabulary of performative surfaces that balance structural efficiency with sensory effect. Furniture and architectural components double as acoustic diffusers, light filters, or structural shells, their densities and patterns algorithmically calibrated to their function. Each printed line becomes an architectural stroke – expressive yet data-driven. This merging of computational logic and material spontaneity generates a new typology of industrial ornamentation, one that arises not from decoration but from the physics of making.

In this sense, the company's practice oscillates between industrial research and poetic fabrication, demonstrating that robotic 3D printing can embody both engineering rigour and artistic sensibility. The robot thus becomes a mediator between algorithm and matter, translating digital intent into tactile presence.

Material Intelligence and Smart Composites

Nagami's ongoing material research expands additive manufacturing into the realm of smart and hybrid composites. By collaborating with Smart Materials 3D, the company has integrated organic residues such as olive pits, coffee grounds, oyster shells, and cork powder into recycled polymers. These combinations yield new mechanical behaviours, tactile qualities, and visual effects, transforming matter into a living archive of its origin.

Each material blend tells a story: Andalusian olive pits evoke Mediterranean landscapes, oyster shells recall marine ecologies, and cork connects to Iberian forests. In this way, industrial production regains territorial specificity. The process embeds geography into the object itself, aligning fabrication with notions of cultural and ecological identity. The introduction of organic matter into industrial polymers creates what could be called geo-material design – a discipline that links local resources to global manufacturing.

This research not only expands the sustainability spectrum but redefines the relationship between nature and technology – suggesting a future where industry speaks in regional accents. It also hints at the emergence of a new material consciousness in design, where environmental ethics and aesthetic innovation converge.

Collaborations and Creative Engineering

Nagami gained international recognition with the VoxelChair v1.0 (2017), designed by Manuel Jiménez García and Gilles Retsin – one of the first pieces of robotic 3D-printed furniture. Now part of the permanent collection of the Centre Pompidou, the chair became an emblem of digital craftsmanship and demonstrated the expressive and structural potential of robotic extrusion at furniture scale. Its layered form embodied both algorithmic rigour and material spontaneity, showcasing how digital fabrication could become an artistic gesture.

Since then, Nagami's collaborations with Ross Lovegrove, Zaha Hadid Architects, Karim Rashid, Patricia Urquiola and Daniel Widrig, among others, have pushed the boundaries of computational design and material performance. These partnerships are not artistic commissions but co-engineering dialogues, where each concept tests the limits of geometry, structure, and code. The Brave New World collection, unveiled at Milan Design Week 2018, showcased this philosophy by achieving museum-quality finishes through 100% recyclable materials.

Nagami's pieces have entered the permanent collections of the Centre Pompidou and the Philadelphia Museum of Art, and have been exhibited at the Victoria & Albert Museum, the Royal Academy of Arts, the Design Museum London, Zaha Hadid Gallery, CaixaForum, and other recognised institutions. These exhibitions have positioned Nagami as both a technological pioneer and a cultural agent. Together, these milestones reaffirm that additive manufacturing belongs as much to cultural discourse as to industrial production.

Sustainability, Customisation, and Efficiency

Nagami's production model demonstrates that sustainability, efficiency, and creative freedom can coexist. Its robotic printing system, free from moulds or heavy tooling, enables agile, low-waste production adaptable to both bespoke projects and medium editions. This method bridges the gap between mass production and artisan craft, allowing clients to create unique collections with reduced environmental and economic impact.

The collaboration with Teatro Pereyra in Ibiza exemplifies this approach: exclusive furniture series of only 250 chairs and 100 tables per design were printed using recycled polymers. In conventional manufacturing, such a short edition would be economically unfeasible – the cost of producing a mould for injection moulding alone would far exceed the viability of a limited run of 250 custom chairs. With robotic 3D printing, however, every piece can be adapted without tooling, enabling high personalisation at an industrial level. This ability to customise shapes, colours, and patterns allows each project to reflect the client's identity – turning production into a vehicle for brand storytelling and spatial differentiation. Similarly, Porsche's The Flat by Macan introduced the B-Loom Chair, a collection of 300 pieces designed by Manuel Jiménez García, translating

Fig.3: VoxelChair v1 - designed by Manuel JG and Gilles Retsin

Fig.4: B-Loom Cgaur - designed by Manuel JG for Porsche

Fig.5: Nagami x Zaha Hadid Architect - Rise Chair

Fig.6: Pereyra - designed by Manuel JG

Fig.7: Nagami Production Facility in Avila Spain

the car's dynamic geometry into a furniture line. The project exemplified how advanced manufacturing can merge automotive precision with domestic scale.

These collaborations illustrate how large-scale 3D printing merges luxury design and sustainable thinking through precise, efficient, and emotionally engaging manufacturing. A parallel philosophy underpins the collaboration with Real Madrid CF. By transforming 80,000 discarded stadium seats from the old Santiago Bernabéu into collectible objects, Nagami created a new category of design memorabilia – merging history, emotion, and sustainability. Such a vast project, involving multiple models and customised variants, would have been economically unviable with injection moulding, as the cost of producing and adjusting moulds for so many unique pieces would have outweighed the production itself. The scale that Nagami achieves, operating with 21 robots, allows it to combine the advantages of mass production with the flexibility of customisation – making large numbers feasible while maintaining individuality. Here, robotic fabrication acts as a medium for storytelling, converting material waste into tangible heritage.

Research and Continuous Evolution

Beyond production, Nagami operates as an active research platform exploring the intersection of AI, computation, and fabrication. Its work extends beyond manufacturing to redefine how design intelligence can evolve through constant feedback and iteration. The company develops AI-assisted design tools, adaptive extrusion algorithms, and multi-material printing workflows that capture data directly from the printing process. This data-driven approach transforms fabrication into a living system, where each print informs the next – generating a self-improving cycle of material and formal innovation. In collaboration with universities, technology partners, and advanced laboratories, Nagami explores the relationship between visual texture, layer behaviour, and mechanical performance. These studies aim to predict how a change in extrusion speed or temperature might affect not only the strength but also the appearance of the final surface. By correlating data across hundreds of prints, Nagami is shaping a new form of material intelligence – one where geometry, thermodynamics, and machine logic evolve together. This constant research

Fig. 8: Nagami x TOFoundation - The Throne

Fig. 9: Nagami x Hassel x TOFoundation - 3D Printed Pavilion

activity has positioned Nagami as a model for the future of architectural fabrication. Its robotic cells function as learning organisms that translate computation into craft, turning technical precision into a form of cultural expression. The company thus contributes to a broader understanding of robotic additive manufacturing as a system of continuous learning, where matter and code are no longer separated but engage in perpetual dialogue.

From Sustainability to Desire

One of the key arguments of Nagami's philosophy is that sustainability will only succeed if it becomes desirable – if it can seduce through its intelligence. Environmental responsibility, for Nagami, must be reframed as aspiration rather than constraint: a field of invention and beauty instead of austerity.

In this context, the company redefines luxury as the harmony between intelligence, efficiency, and emotion. Every printed chair, table, or architectural panel is conceived as a synthesis of ethics and aesthetics. A wall panel made from recycled polymer and olive stone powder is not valuable simply because it reuses waste; it is valuable because it expresses a story – the fusion of ecology, technology, and imagination into a single form. This reframing transforms ecological design into cultural aspiration. Nagami's approach demonstrates that circular design can move beyond compliance into fascination. By turning materials with previous industrial lives into luminous, tactile objects, the company proves that sustainability can be sensual, vibrant, and collectible. This vision challenges the additive manufacturing community to expand its evaluation criteria: from technical performance to aesthetic resonance – from efficiency to emotion. Surfaces, toolpaths, and colour gradients become part of a new metric of desirability, turning circular manufacturing into cultural production.

Toward a New Industrial Aesthetic

Nagami's work signals a broader cultural transformation within additive manufacturing – a shift from optimisation to expression. As robotic systems evolve in speed, precision, and autonomy, the next revolution is not mechanical but humanistic: how to make technology an extension of human creativity rather than a replacement for it.

The company proposes that beauty is a measure of intelligence: when process, material, and purpose align, sustainability becomes visible. Every object Nagami produces – from the Voxel Chair to a hotel wall panel or a sculptural façade element – embodies this synthesis. Each layer records the energy of its making, turning manufacturing into a temporal, almost performative act.

In this sense, Nagami contributes to a new industrial aesthetic – one that fuses computation and sensibility, automation and authorship. Its robots operate not as anonymous labour but as collaborators in a creative dialogue, enabling an unprecedented degree of expressivity in industrial production. Additive manufacturing thus becomes a medium of meaning: a way to merge culture, ethics, and beauty into the very fabric of matter.

Conclusion: The Future Layer by Layer

From Waste to Luxury ultimately tells a story about transformation – of materials, processes, and values. It argues that advanced manufacturing can transcend efficiency to achieve emotion and significance, becoming a cultural practice in its own right. When guided by vision, technology is not a neutral tool but an expressive medium – one capable of shaping the aesthetics and ethics of our century. Nagami's trajectory offers a reflection on the near future of additive manufacturing: a future where sustainability and sophistication merge, where material data carries emotional weight, and where the factory floor becomes a site of imagination. This evolution marks the transition from industry as repetition to industry as creation, from linear consumption to circular expression.

In this new paradigm, waste is no longer an endpoint but a beginning – the first layer of something extraordinary, where beauty, intelligence, and responsibility coexist within every print.

Fig. 10: Nagami - Porsche Flat by Macan

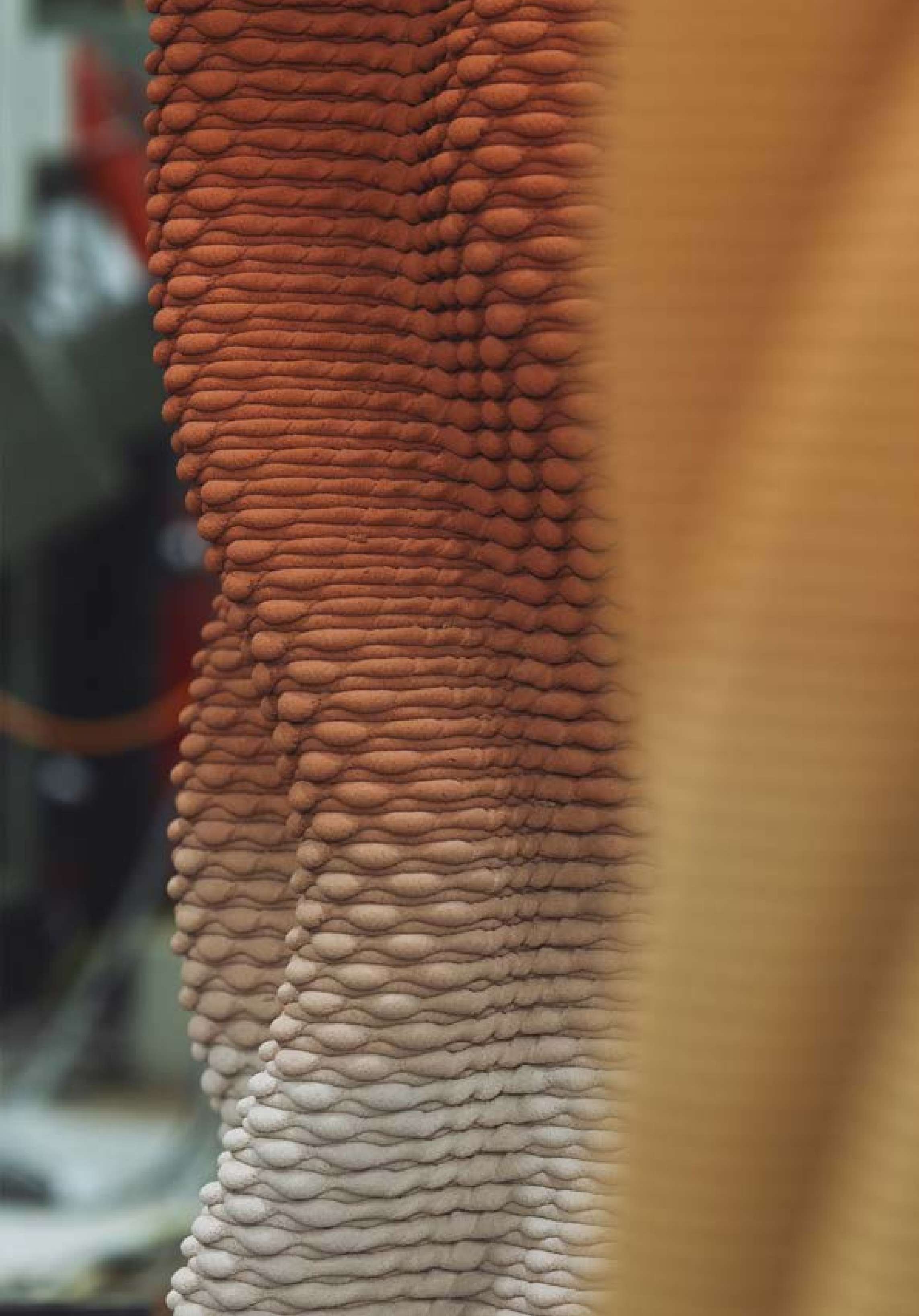
Fig. 11: Nagami x StudioRRR - Ecoalf Flagship Las Rozas

PROJECTS

AMBER PILLAR

Vertico
Vertico

The Amber Pillar is a sculptural 3D-printed column that blends structural integrity with artistic expression. Its form is defined by a woven-like pattern that spirals upward, evoking a sense of movement and craftsmanship. Printed with a gradient of warm, amber-inspired tones, the column captures the richness of natural materials while remaining fully rooted in digital fabrication. This piece exemplifies Vertico's commitment to pushing the boundaries of concrete printing. Free from traditional molds, the Amber Pillar demonstrates how parametric design and robotic control can produce unique, load-bearing elements that elevate both structure and aesthetics. Behind the aesthetic is a structurally optimized geometry, made possible by our advanced printing system and research-driven reinforcement strategy. The result is a column that is both practical and poetic–designed to perform and built to inspire. The Amber Pillar is part of an ongoing exploration into customized architectural components that rethink how we build: with more freedom, more beauty, and more purpose.



THE NESTING BRICK

Technical University of Darmstadt, Generative Desing Lab
Alexander Wolf, Ulrich Knaack

This case study investigated the potential of additive manufacturing methods for creating bespoke ceramic building components. Although the exhibited custom brick-geometry resembles an already market-available product, Hagemeister GmbH's Nesting-Brick, the production technology used to create it treads new paths. By using a 3D-printer to shape these bespoke components, the predominant process, a fully manual and artisan modelling was bypassed, leading to increased efficiency in production. Being part of a PhD-thesis, the developed methodology may also serve as a blueprint for the creation of a multitude of other articulate ceramic components, as it allows for great range of adaptions in terms of geometry and surface-finishing. Therefore, the shown exhibit does not only display the processes' capability to replace shortage in skilled labor, but also gives a glimpse on the new freedom of form it is coming with. In particular, the targeted use of AM-shaped components could even usher in a new era of brick architecture, which would be characterized by digitally designed ornamentation.

SEPTA

etcetera
Ariane Stracke-Henderson, Rob Henderson

3D printing is a technology in line with a 20th century furniture innovation: fiberglass. The Eames got it right in then, combining the high-tech production of the time with design and comfort. 3D printing is revolutionizing design like fiberglass did then. The challenge is achieving elegance, lightweight, and comfort with 3D printing on an industrial scale. We looked into successful existing rocking chairs. We noticed similarities in the angles of the seat, back, and radius of the rocking rails. As a perk, we wanted our chair to rock in all directions and spin. We explored possible shapes and also the 3D printing technology to produce the chair. Robotic 3D printing is like drawing a house without lifting the pencil: it requires one continuous motion.

Technically, the Septa rocking chair is composed of two curves layered to create a continuous material loop, so the robot doesn't stop in between. The infill in a 3D-printed product is an important aspect to consider during the design process, so the infill of the Septa Chair is an integral part of the design. Usually, the infill is generated by software. But in this case, we designed the infill ourselves because it is an integral part of the chair design. These technological challenges created an excellent opportunity to work more closely with Nagami. Because we wanted to do something that could not be done in regular production - namely, print a single curved chair - Nagami had to expand on its normal production process.

ACOUSTIC PANELS

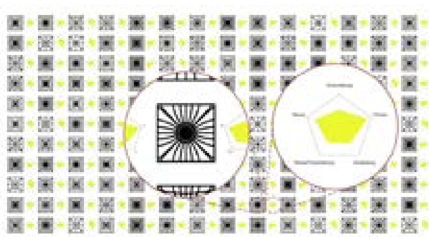
UNSW Sydney, Arch_Manu
M. Hank Haeusler, Dagmar Reinhardt, Charlotte Firth, Louis Lamont, Densil Cabrera, Ivana Kuzmanovska

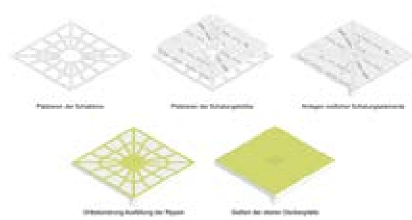
An increase in flexible working environments has increased the demand for rooms with video conferencing facilities. Yet while several of these rooms could be equipped with video conferencing equipment such as large-scale TVs, cameras and audio equipment no acoustic improvement has been offered. This renders these rooms as an unpopular option for online meetings as the remote located party has difficulties in understanding what has been said. Following acoustic testing of an existing meeting room at the University of New South Wales we developed a computational script that generated a complex curved geometry for reflection and a small openings for absorption. For the fabrication of the acoustic panels recycled plastic and 3D printing was selected to test of plastic waste could be employed as acoustic materials even if traditionally a 'hard surface' material is not considered as an optimal material for acoustic improvements. Through our script and fabrication, we could demonstrate that plastic waste offers acoustic improvements when combined with computational design and robotic fabrication.

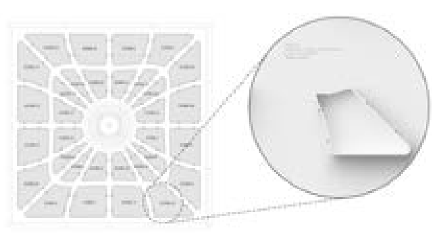
TOPOLOGY-OPTIMIZED 3D-PRINTED CONCRETE SLAB

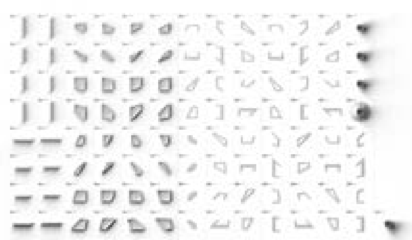
Technical University of Darmstadt, Institute of Constructive Design and Building Construction (KGBauko)
Stefan Schäfer, Nikola Bisevac

In the summer semester of 2025, the Technical University of Darmstadt, Institute of Constructive Design and Building Construction (KGBauko), in close collaboration with Sika Germany, Riedel Bau Group, and Staikos 3D, initiated a pioneering project in the field of 3D Concrete Printing (3DCP). The project focuses on the development and realization of a topology-optimized concrete slab with a span of 5 x 5 meters, whose formwork is entirely produced using 3D printing technology. A major challenge in applying additive manufacturing in construction is the lack of standardized norms and building regulations. To address this, the project employs an innovative approach: the 3D-printed formwork serves as a lost formwork, reinforced with conventional steel, and subsequently filled with cast-in-place concrete. This approach combines the advantages of 3DCP with current building code requirements, ensuring a compliant and practical implementation. The 3D-printed formwork serves a dual function: it defines the ribbed geometry of the slab while also illustrating the internal force flow within the structure. Additionally, additive manufacturing allows for complex geometries that would be difficult or impossible to achieve with traditional formwork methods. This results in a material-efficient, resource-conscious, and design-flexible construction method that aligns with sustainable building principles. The full-scale demonstrator is currently under construction at the Riedel Bau Talentfabrik, with completion planned by the end of September 2025. This project represents a significant step toward the practical integration of 3DCP technologies in modern construction.









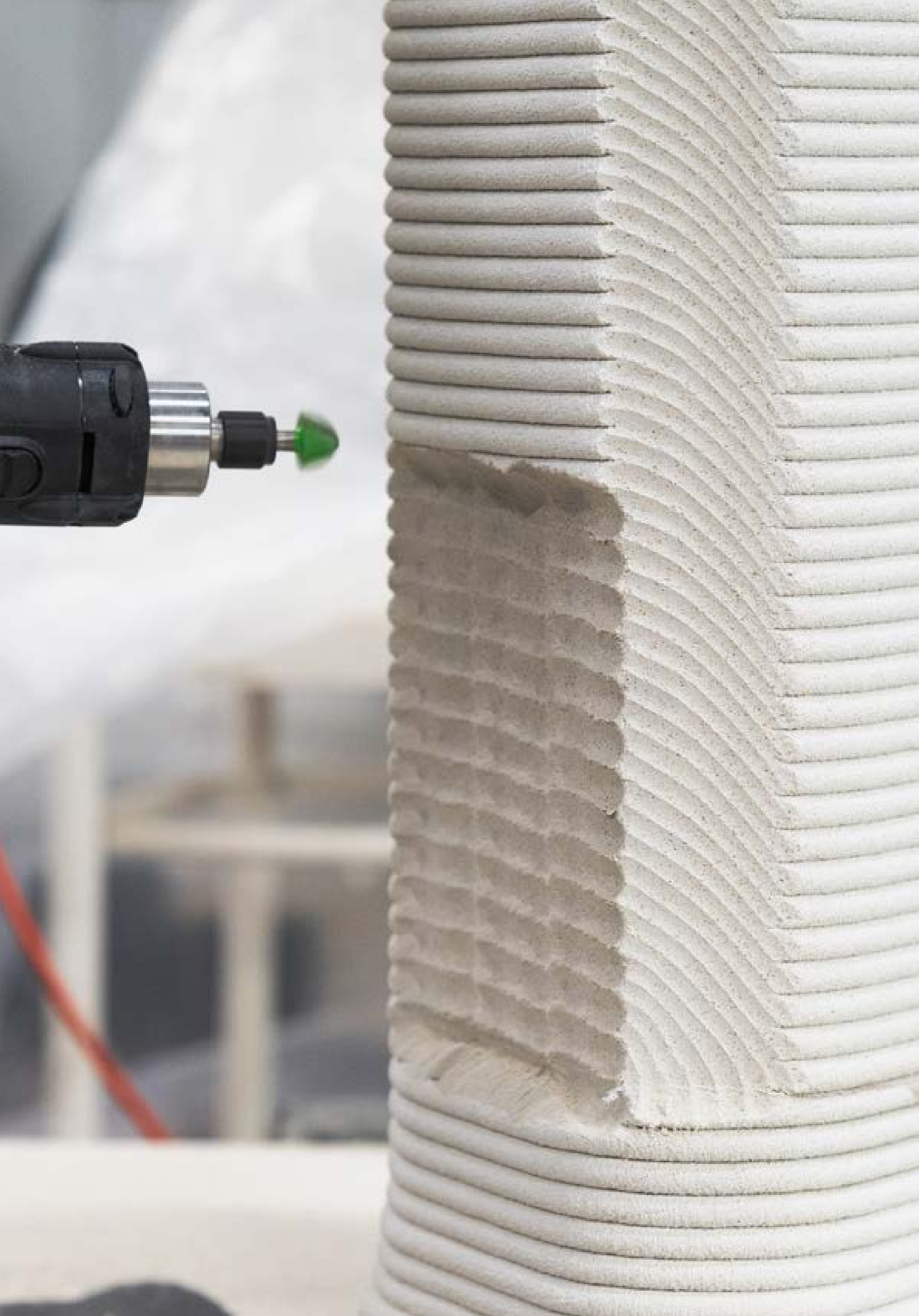
MODERN RENAISSANCE: ROBOTIC MILLING MEETS 3D CONCRETE PRINTING

Vertico
Vertico

Vertico is pioneering a new chapter in 3D concrete printing by introducing robotic milling as a post-processing method. This innovation enhances the level of detail and surface quality achievable with printed concrete and opens up design possibilities previously limited by the extrusion process alone.To demonstrate this capability, Vertico produced a short concrete column featuring several distinct milling patterns. Each section of the column showcases a different surface treatment, ranging from fine textures to bold grooves, highlighting the precision and versatility of the milling process.

Robotic milling allows for:
- High-resolution detailing beyond the limits of nozzle size
- Smooth finishes and refined edges
- Modular connections with millimeter accuracy

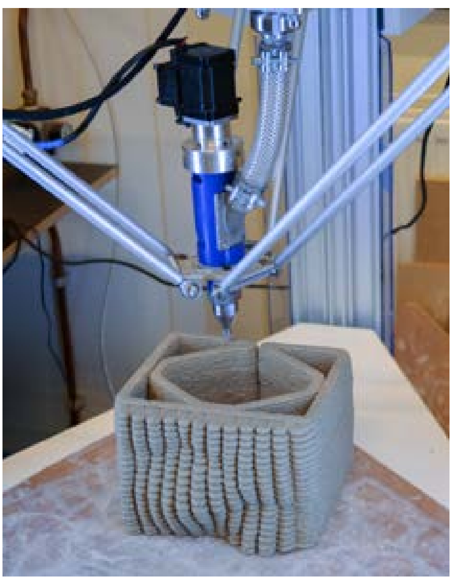
By combining printing and milling, Vertico bridges the gap between rough formwork and architectural craftsmanship. The column serves as a research piece, reflecting ongoing efforts to fine-tune milling settings and adapt to conditions such as drying time and surface hardness. This hybrid process holds significant potential for architecture, restoration, and design - bringing concrete into a new era where digital fabrication meets sculptural precision.



CONTROLLING ROUGHNESS

Delft University of Technology (Industrial Design Engineering), collaboration with Omlab
Carmen Enríquez, Zjenja Doubrovski, Eliza Noordhoek

This project explores the potential of bio-circular materials for architectural applications, focusing on their use in fabricating indoor walls. To conduct this research, a material recipe by the studio Omlab was implemented. The project investigates how 3D printing can be leveraged to actively design and control material properties, to enhance its unique opportunities. By varying 3D printing toolpaths, the project aims to exploit the relationship between 3D printing parameters and material roughness as a design opportunity. Through an experimental methodology, the project demonstrates that surface roughness is highly dependent on toolpath design. Using the impedance tube method for absorption coefficient measurement, the project reveals the influence of 3D printing parameter variations on the acoustic absorption properties of the bio-circular material. The findings of the project show that additive manufacturing enables the design of multi-scale surface roughness that influences acoustic performance. This opens new pathways for 3D printing with bio-based materials in architectural contexts. Positioning roughness as an asset controlled to meet architectural needs.



SELECTIVE ROBOTIC RAMMED EARTH

Technische Universität Braunschweig, Institut für Tragwerksentwurf
Samim Mehdizadeh, Joschua Gosslar, Noor Khadar, Norman Hack, Harald Kloft

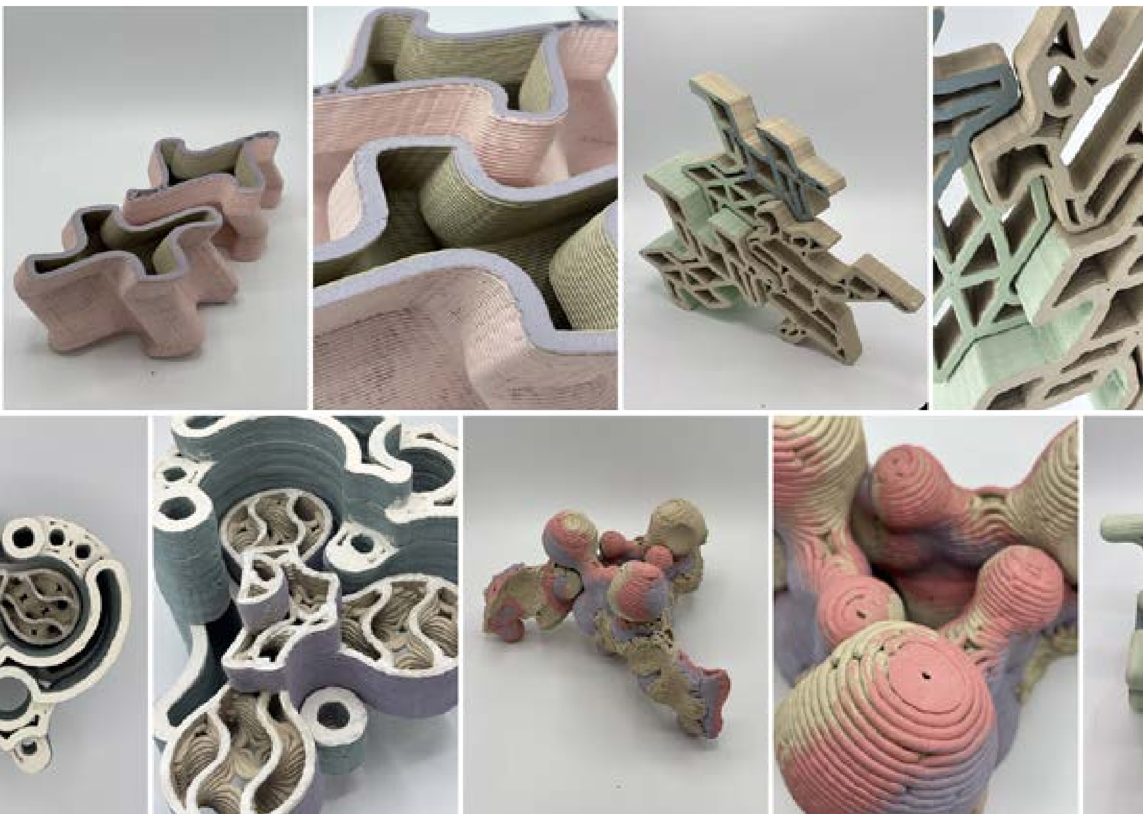
This paper introduces Selective Robotic Rammed Earth (SRRE), a novel robotic fabrication method for discretized earthen-based construction. The research positions SRRE within the urgent need for sustainable, low-carbon construction technologies, emphasizing the integration of traditional earthen techniques with contemporary robotic processes. Earthen materials, and particularly rammed earth, offer significant environmental advantages such as low embodied energy, recyclability, and reduced carbon footprint, while providing acceptable structural performance. However, conventional rammed earth construction is constrained by the dependence on heavy, wasteful and material-intensive formwork, intensive manual labour, and geometric limitations imposed by the formwork itself. SRRE eliminate material intensive formwork of rammed earth and replace it with robotic selective ramming process. This robotic fabrication process transfers the complexity from formwork system to selective ramming and enable higher level of geometric freedom.

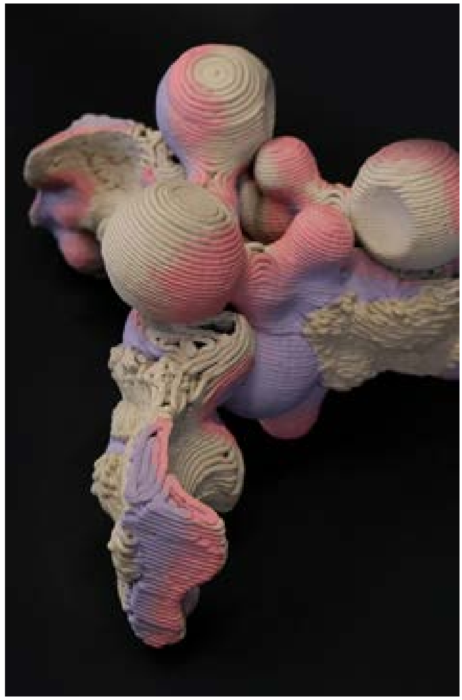

Customized

ANOTHER CERAMIC BRICK IN THE WALL

Universität Innsbruck, cera.LAB, exparch.hochbau
Jan Contala, Marjan Colletti

This research investigates ceramic 3D printing as a means of redefining the brick within contemporary masonry. Focusing on modular, mortar-free units, the work explores how ceramic components can function as sustainable, adaptable building blocks within a circular economy. The study examines strategies for disassembly and reconfiguration, highlighting ceramics' potential to extend beyond conventional structural roles into multifunctional and expressive applications. By merging computational design with the craft of clay, the research develops prototypes that test complex geometries, interlocking systems, and innovative surface treatments. The outcomes challenge traditional perceptions of the brick as a repetitive unit, instead positioning it as a versatile system that integrates performance, sustainability, and design expression. Ultimately, the work demonstrates how digital fabrication can transform one of the world's oldest building materials into a platform for future architectural innovation.





BIOBASED FACADE PANELS: SUSTAINABLE DESIGN THROUGH LARGE-SCALE AM

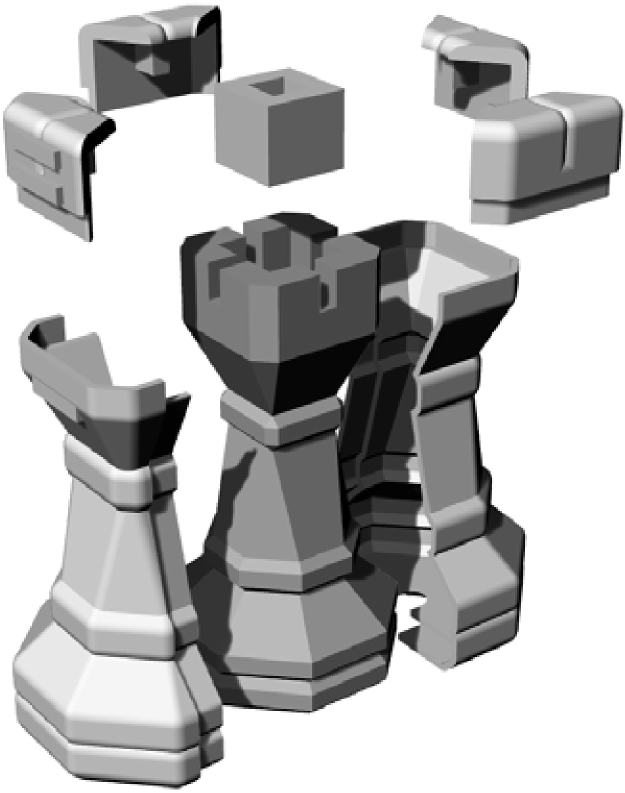
AITIIP, R&D Department
Raquel Navarro, Iván Monzón, Alberto Laguia, Jose Antonio Dieste

This research explores the architectural potential of sustainable materials in Additive Manufacturing. Using Large-Scale Additive Manufacturing (LSAM), façade panels are fabricated from a bio-composite of cellulose acetate reinforced with hemp fibres, offering a renewable alternative to conventional construction materials. A standout prototype features a visible transition from virgin polymer to composite, enabling differentiated mechanical and thermal properties within a single element. This material gradation allows for tailored performance depending on the panel's zone, enhancing functionality and energy efficiency. The panels are modular, designed with a rear interlocking system compatible with standardized façade profiles. This ensures scalable deployment across building envelopes while maintaining ease of installation and structural integrity. Developed under the ATRIUM initiative, the project extends LSAM applications beyond façades to include green walls, reinforcing the versatility of bio-composites in sustainable architecture. The initiative aims to demonstrate how material innovation and additive manufacturing can drive environmentally responsible construction practices. By leveraging material transitions and modular design, the research proposes multifunctional architectural components with tailored properties and industrial compatibility. This work aligns with broader efforts in the sector to optimize additive manufacturing processes through material development and hybrid fabrication strategies, as seen in recent initiatives by Aitiip Centro Tecnológico.

DIGITALFORMWORK - PARAMETRIC GENERATION OF 3D-PRINTABLE CONCRETE FORMWORK

Technical University of Darmstadt, Generative Design Lab
Simon Hausknecht, Alexander Wolf, Ulrich Knaack

DigitalFormwork was developed to facilitate the digital design process of 3D-printed formwork for concrete applications. Within the construction sector, considerable effort has been directed toward implementing large-scale concrete 3D printers that produce concrete elements directly – a technology limited in the geometries it can achieve. An alternative approach is presented here: 3D printing the formwork, rather than the object itself, enables a high degree of design freedom, since any shape that can be cast and subsequently demolded without damaging the concrete body can, in principle, be realized. In this way, modern 3D modeling software expands the creative potential of architectural design through the generation of complex shapes. DigitalFormwork, developed as a plug-in for Rhinoceros 3D/Grasshopper, provides a range of tools intended to support users in parametrically generating formwork parts suitable for 3D printing. Key features include assistance in modeling material-efficient formwork components, verifying their manufacturability with FDM printers, and simulating the demolding process to identify potential collisions. By 3D printing formwork instead of the concrete part itself, the creative freedom that has long been available with other materials can now be harnessed for concrete. DigitalFormwork empowers architects, engineers, and builders to unlock expressive, practical, and versatile designs by simplifying the path from digital vision to physical form.



BRICK BY BIT

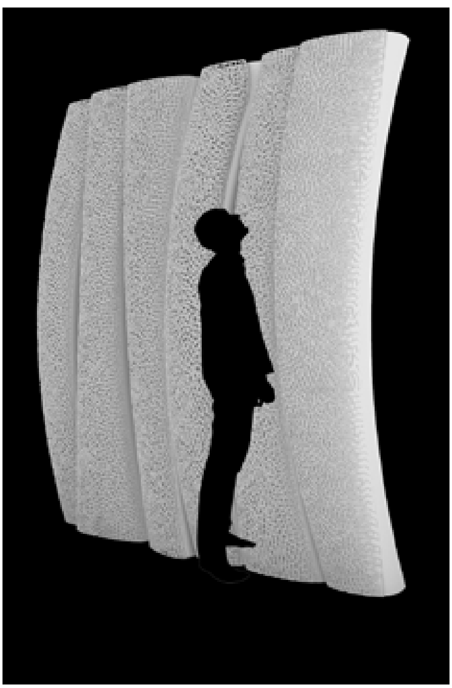
TU Berlin, collaborative design labratory (CoLab)
Victoria Roznowski, Ignacio Borrego, Ralf Pasel, Gaizka Altuna Charterina

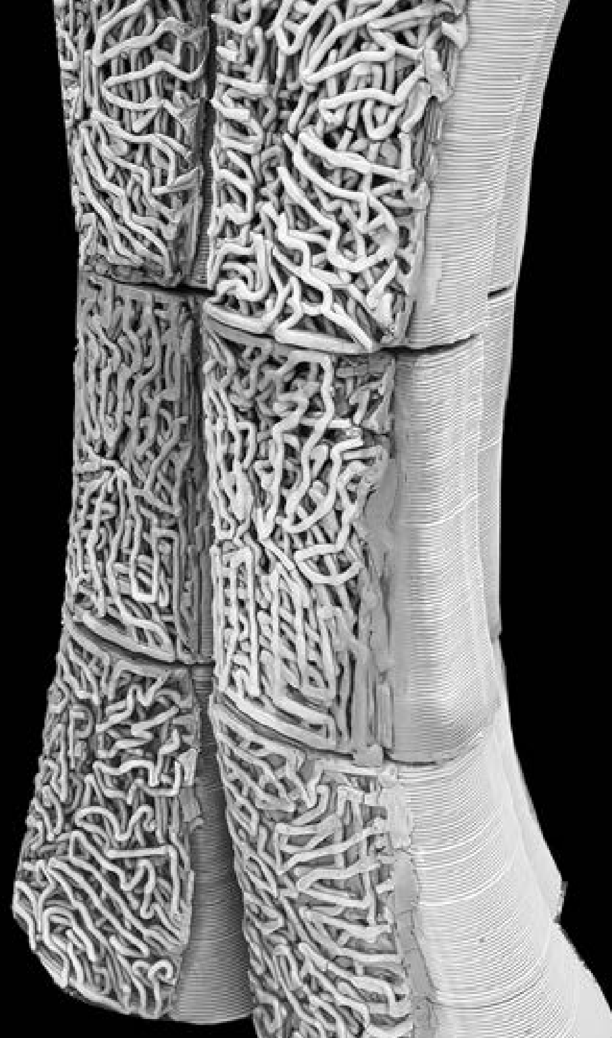
Brick By Bit is a modular 3D-printed façade system that unites aesthetic, ecological, and thermal performance within a single architectural component. Developed through computational design and additive manufacturing, the project explores how complex geometries can be optimized for energy efficiency while integrating ecological functions such as façade greenery and rainwater management. The system consists of three specialized brick types: planting bricks with integrated pockets for vegetation, water-channeling bricks that guide rainwater to plants for natural irrigation, and ventilated bricks that enable façade ventilation for thermal regulation. Their interlocking geometry eliminates the need for mortar, ensuring full disassembly and reuse. A custom Grasshopper-based workflow, combining generative algorithms with FEM thermal simulations, enabled iterative optimization of cavity patterns and insulation strategies. Prototyping with a Delta WASP 2040 clay 3D printer validated printability, texture design, and assembly at 1:2 scale. Brick By Bit demonstrates how digital design and additive manufacturing can redefine masonry for the 21st century, creating building envelopes that actively contribute to energy efficiency, biodiversity, and resource-conscious construction.

SILENT SILHOUETTES - ADDITIVELY MANUFACTURED ACOUSTIC ABSORBERS MADE OF CLAY

Technical University of Darmstadt, Digital Design Unit (DDU)
Stefanie Appelgrün, Oliver Tessmann, Max Benjamin Eschenbach

This project investigates the potential of additively manufacturing acoustic absorbers from clay. The goal is to replace fossil-based sound absorbers by developing a mono-material, sustainable, and acoustically effective structure that does not require additional carrier materials or composites. Since clay inherently exhibits low sound absorption, the improvement of acoustic performance in this study was achieved primarily through the design of geometry rather than the material itself. The developed geometry is based on a growth algorithm that creates complex pore spaces in the inner structure. Methodologically, the approach is supported by computer-based simulations, impedance tube measurements, and reverberation chamber tests that confirm the prediction of the acoustic performance. The developed process chain demonstrates the potential of additively manufactured clay structures as a sustainable alternative to conventional acoustic solutions.





DIGITAL CERAMIC ROOFTILES

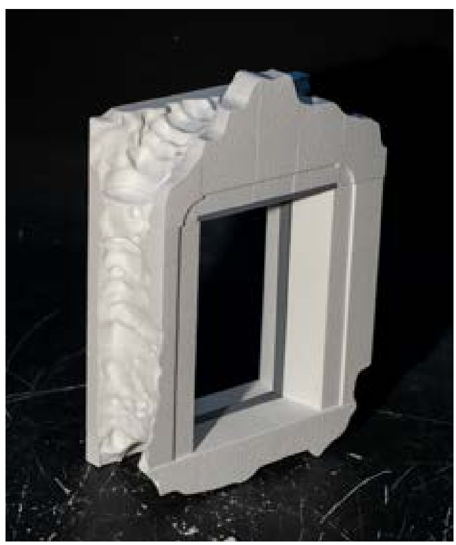
Technical University of Darmstadt, Institute of Structural Mechanics and Design (ISM+D)
Henrik Hoffmann, Alexander Wolf, Ulrich Knaack

This study addresses the reproduction of medieval roof tiles using additive manufacturing processes for ceramic building materials and examines their potential for the preservation of architectural heritage. Following a brief contextualization of the topic within additive manufacturing and heritage conservation, a range of historical tiles with different geometries were selected, digitized, and remodeled in CAD. These were then reproduced using ceramic 3D printing to evaluate the suitability of this technology for the complex geometries of historical building components. The evaluation of the results shows that the reproduction of historical building fabrie through additive manufacturing is fundamentally feasible, although a geometry-dependent process analysis is necessary to address the specific challenges involved. It can therefore be concluded that reproducible methods can be developed for certain geometries, while at the same time new research questions arise, particularly concerning the limitations of additive manufacturing with ceramic materials. In doing so, this work contributes to the further development of methods in the field of heritage conservation and opens up perspectives for the sustainable preservation of historical building fabric.

LAYER BY LAYER

Delft University of Technology, Faculty of Industrial Engineering, collab: Faculty of Architecture and the Built Environment
Nikolas Barrera Parisakis

This project explores how Large-Scale Additive Manufacturing can support the preservation and Adaptive Reuse of vernaular architecure by combining repair and adaptation into a single intervention. A heritage site in the island of Thirasia, in Greece, was selected and documented through on-site analysis and 3D scanning to understand its cultural, historic, and architectural context.The findings of this research informed the development of a 3D-printed proposal that reintroduces missing fragments into the building envelope and facilitates the parametric reconstruction of an entire village comprised of more than 100 underground houses. The 3D-printed intervention uses a pozzolanic mortar made from volcanic ash sourced on-site. This solution is inspired by traditional building techniques, enabling the preservation of local craft in the reconstruction process. The resulting prototype demonstrates how LSAM can produce site-specific components that incorporate local materials and craft, as well as facilitate the simultaneous preservation of multiple architectural units through 3D scanning and parameterization. The project combines material experimentation with the translation of unique features enabled by vernacular building techniques into the digital fabrication realm, effectively proposing a novel approach to the revitalization of heritage sites. Merging restoration and innovation, it shows how LSAM can enhance the usability of historic buildings while maintaining their cultural significance and contributing to the historical layering of interventions over time.



MULTI-MATERIAL ADDITIVE MANUFACTURING WITH BIOMATERIALS

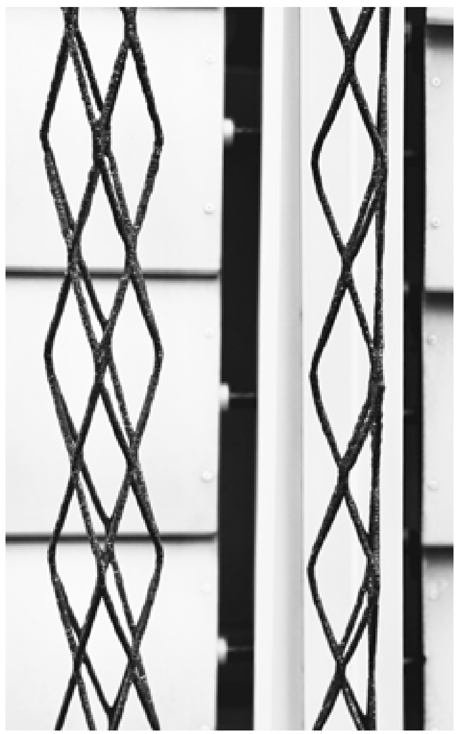
University of Innsbruck, Department of Experimental Architecture,
Robotic Experimentation Laboratory (REX|Lab)
Kilian Bauer

Multi-Material Additive Manufacturing with Biomaterials presents a promising pathway to overcome the inherent limitations of biological materials in additive manufacturing and extend their field of application to the built environment. By combining materials with complementary properties–for instance, pairing robust, plant-based thermoplastic biocomposites with fragile yet fully biodegradable materials–this approach enhances both structural integrity and environmental responsiveness. The prototype presented in this study introduces a novel fabrication strategy that alternates two layers of a compostable biomaterial paste (wood sawdust bound with biodegradable methylcellulose) with one layer of a plant-based thermoplastics (Tecnaro Arboblend). This method enables the 3D printing of design objects and architectural components at scales previously unattainable with biomaterials alone, which would collapse under their own weight. The selected materials serve as representatives of broader material families: any plant-fiber and biological binder biomaterial, or any plant-based thermoplastic, could substitute for the demonstrated examples. Both families support a fully circular material life cycle, as they can be mechanically or physically separated, shredded and recycled. While the presented work highlights the potential of multi-material strategies to address critical challenges of performance, reliability, and scalability in biomaterial 3D printing, it also underscores the need for tailored fabrication technologies, appropriate regulatory frameworks, and adapted testing protocols to allow additive fabrication to reshape our built environment with novel, future-oriented material systems. By advancing hybrid 3D printing approaches, this work points toward a paradigm shift in sustainable architectural production, enabling novel material applications and fostering more ecologically conscious construction practices.

D-POLES - DIGITAL DESIGN AND FABRICATION OF 3D-PRINTED STEEL LATTICE STRUCTURES

University of Bologna, Department of Civil, Chemical, Environmental and Materials Engineering
Vittoria Laghi, Elisabetta Savino, Giada Gasparini, Tomaso Trombetti

Lattice materials and structures have grown interest over the years due to their high strength-to-weight ratio and tunable mechanical properties, making them suitable for applications requiring lightweight and adaptable structural elements. With the advent of large-scale metal 3D printing technologies, such as Wire-Arc Additive Manufacturing, lattice structures could be scaled from micro- (at the material scale) to meso-scale (at the structural element scale). This research investigates the structural behavior of a new generation of 3D-printed diamond-shaped lattice steel columns, focusing on their unique mechanical properties and performance under compression loading. The work provides an overarching study on these new structural elements, from the conceptual definition to analytical, experimental and numerical investigations on various configurations of 3D-printed diamond-shaped lattice steel columns.



A FLEXIBLE MOLD FOR CUSTOMIZED 3D-PRINTED FACADE PANELS

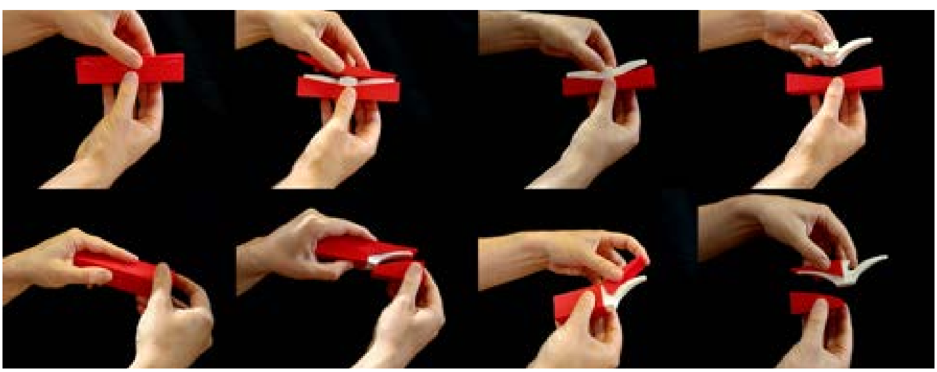
TU Wien, Art and Design
Florian Rist, Marco Palma, Michaela Nömayr, Dominik L. Michels

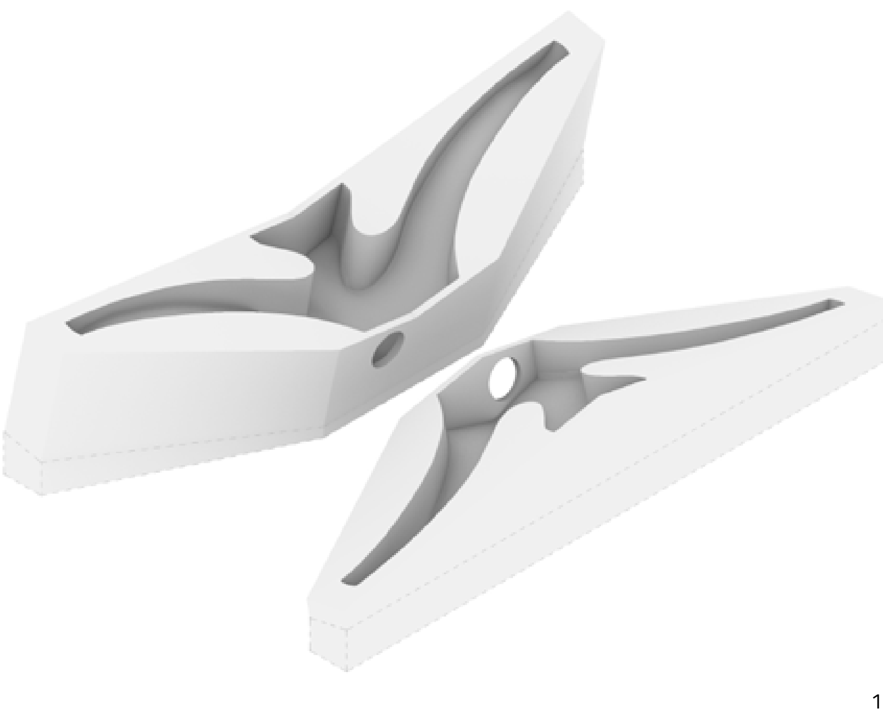
Architectural surface panelling often requires fabricating molds for panels, a process that can be cost-inefficient and material-wasteful when using traditional methods such as CNC milling. We introduce a novel solution to generating molds for fabricating 3D printed architectural panels. At the core of our method is a machine that utilizes a deflatable membrane as a flexible mold. By adjusting the deflation level and boundary element positions, the membrane can be reconfigured into various shapes, allowing for mass customization with significantly lower overhead costs. We devise an efficient algorithm that works in sync with our flexible mold machine that optimizes the placement of customizable boundary element positions, ensuring the fabricated panel matches the geometry of a given input shape.

DENKMALBIM

Technical University Darmstadt, Institute of Structural Mechanics and Design (ISM+D)
Juan Ojeda, Daniel Andrade Almeida, Alexander Wolf, Ulrich Knaack, Laura Valderrama Nino, Sabrina Becker, Jascha Brötzmann, Uwe Rüppel, Yuri Nasonov, Abhinay Kumar, Jochen Hölscher, Natchai Suwannapruk, Jens Böke, Nicolas Weidinger, Florian Grosse, Benjamin Sattes

Building Information Modelling (BIM) provides a powerful digital framework for construction and design of new architectural projects, although it is not widely used for the restoration of heritage buildings. The complex geometries, fragmented structures, and need for historically accurate reconstructions have limited its adoption in this field. The DenkmalBIM platform addresses these challenges by extending BIM to heritage restoration and creating an end-to-end process that links geometry capture, digital reconstruction, and fabrication of components. The workflow begins with high-precision 3D scanning methods, such as terrestrial laser scanning, structured light scanning, and photogrammetry to capture the geometry and material properties of historic elements. These scans are processed within the BIM environment, cleaned, and converted into parametric models. Standardization algorithms ensure data compatibility, enabling smooth transfer between structural analysis, design, and fabrication tools. Within this environment, restoration tasks are planned and simulated virtually. Architectural components are reconstructed by combining scan data with reference models, ensuring accuracy even when originals are fragmented or degraded. Each digital object is enriched with metadata, material composition, surface texture, color, and spatial coordinates, providing a comprehensive dataset for both design and fabrication stages. The final stage is the fabrication of replacement parts through additive manufacturing. The platform generates optimized geometries for 3D printing, considering tolerances, material properties, slicing orientation and mechanical performance. Depending on requirements, components or casting molds can be produced using polymer-based printing (FDM), clay extrusion, or advanced methods such as binder jetting or selective laser sintering (SLS) for architectonic elements. By combining 3D scanning, BIM-based modelling, and additive manufacturing in a single workflow, the DenkmalBIM platform creates a coherent digital pipeline. This approach not only accelerates heritage restoration but also increases precision, ensures historical accuracy, and supports scalable, on-demand production of architectonic parts.





ADDITIVE MANUFACTURING WITH RECYCLED POLYMERS AND CALCIUM CARBONATE FROM SHELL WASTE

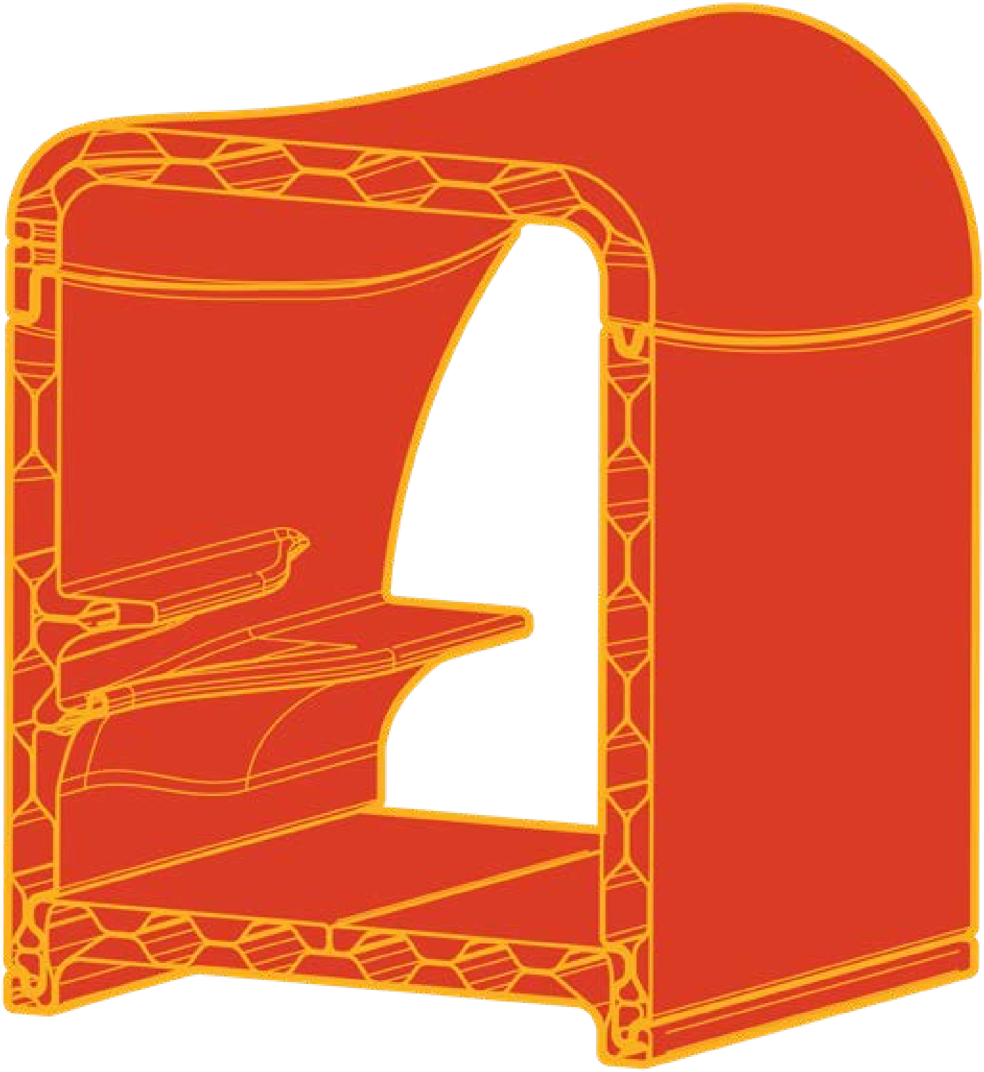
Universidad Adolfo Ibañez, LAMA, Fablab UAI, Designlab UAI
Diego Trucco, Juan Cristobal Karich, Lucas Helle, Francisco Cruz

Our project pairs additive manufacturing with circular materials recovered from the Chilean coast to produce slender architectural columns. Each ~2 m tall column is printed in a single pass using a pellet-fed robot extruder and a compound of recycled polypropylene (rPP) and calcium carbonate ($CaCO_3$) derived from discarded shells. The rPP comes from programmes that collect marine plastic waste such as ropes and nets; after shredding and pelletizing, these streams are blended into high-quality recycled polymer pellets and provide full traceability from collection to final product. Each kilogram of this material prevents about 0.97 kg of CO_2 emissions compared with virgin resin. The $CaCO_3$ filler originates from mussel shells that are milled and calcined to produce a highly reactive, soluble lime. We repurpose this bio-based mineral as a reinforcement that stabilises the rPP during deposition and reduces warping while imparting a speckled, stone-like finish. The results feature precisely tuned wall thicknesses and internal ribbing designed to maximise stiffness, minimise weight and enable continuous extrusion; digital design algorithms optimise toolpaths and structural performance. By transforming ocean plastic and shell residues into load-bearing elements via robotic 3D printing, the project illustrates a viable pathway toward circular building components with a low carbon footprint and transparent supply chain, aligning with the BE-AM vision for sustainable fabrication.

WOHN DEMONSTRATOR - CONSTRUCTION AND REALISATION OF A 3D-PRINTED HOUSING MODULE ON A 1:1 SCALE

Technische Hochschule Lübeck, Architecture and Civil Engineering
Benjamin Spaeth, Michael Herrmann, Anton Brodmann, Sascha Wunderlich, Christoph Schult, Tabea Stannek, Morten Bøve, Matúš Uríček, Daviid Ranløv

The WOHN Demonstrator is based on the results of the WOHN Design Contest, a collaborative semester project and ideas competition for 3D-printed housing module concepts. A team of students led by Prof. Dr.-Ing. Benjamin Spaeth, Prof. Dr.-Ing. Michael Herrmann, Sascha Wunderlich M.A. and Anton Brodmann M.A. refined the most promising approaches to develop a novel construction system for 3D-printed modular housing. The concept was implemented as a demonstrator in close collaboration with the company WOHN A/S at their fabrication facilities in Herlufmagle, Denmark. The work should be continued by further cross-border exhibitions, research investigations and following collaborative projects. The exemplary module on a 1:1 scale consists of 4 segments and has an overall size of 3.4 x 2.6 x 2.4 m (H x W x L). The weight is about 500 kg/segment (2 t/ module). The printing material consists of recycled nylon and recycled glass fibre with a high strength. It is fully recyclable (grinded, re-pelletized and printed again) and has a density of 1.51 t/cbm. The 3D printer at WOHN A/S managed a print speed of max. 250 mm/s and completed each segment in about 14 h printing time (50 h/module). The 3D printing was executed with a 5mm nozzle and a printing bead of 2.8 x 8.4 mm (H x W). The demonstrator features a complex double-curved geometry, functional integration of furniture, integrated chambers for insulation, cable and installation routing as well as interlocking mechanisms for an easy assembly.



DISCRETE LANDSCAPE

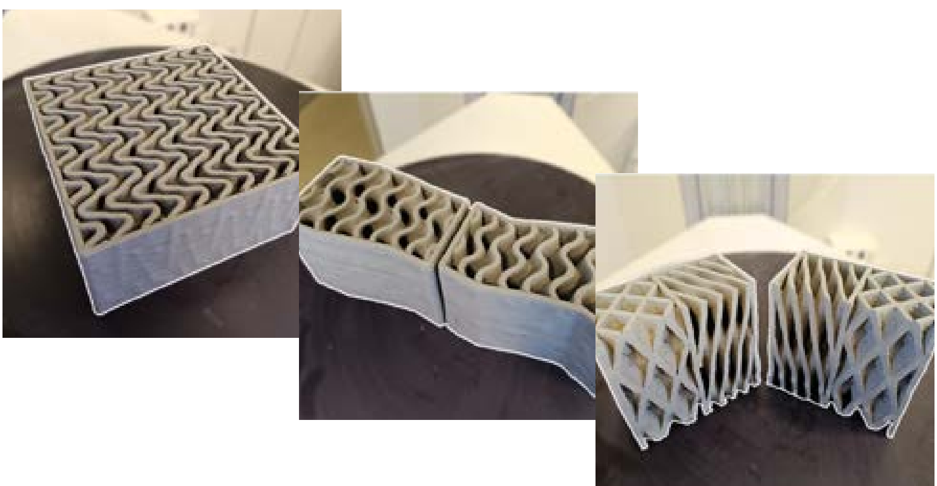
Mario Cucinella Architects, Erratic, Calchera San Giorgio, PoliMi, Mario Cucinella Architects R&D Unit
Mario Cucinella, Lori Zillante, Lapo Naldoni, Massimo Visonà, Gianni Nerobutto, Marco Imperadori

Discrete Landscape, designed by Mario Cucinella Architects for Arte Sella, is a site-specific installation that investigates how additive manufacturing can redefine the relationship between architecture, landscape, and material experimentation. Positioned along the stream at Villa Strobele (Italy), the work creates a sinuous path leading into a contemplative cavity, a spatial gesture that frames fragments of forest, water, and sky. For MCA, the challenge lies in translating the monumental scale of the alpine context into a built form where artificial elements act as a synthesis of thought and matter. The installation consists of 415 blocks across 58 modular typologies, geometrically inspired by basaltic columns. Each module is digitally designed to interlock without mortar, reinterpreting dry-stone techniques through computational design and robotic precision. This modular logic allows the structure to be both self-supporting and fully reversible, highlighting the adaptability of 3D-printed construction systems. The production was executed by Erratic, using a robotic arm equipped with its proprietary extrusion and pumping system engineered for high-viscosity, fluid-dense mixes. The mortar, created with Calchèra San Giorgio and the Politecnico di Milano, integrates natural lime, local aggregates, and industrial by-products such as Adamello tonalite waste and rice husk ash. The resulting composite provides durability, pozzolanic performance, and a porous texture closely attuned to the chromatic tones of the valley. By reducing transport, minimizing waste, and exploiting the precision of additive fabrication, Discrete Landscape demonstrates the technical potential of 3D printing in architecture as both a structural strategy and a sustainable approach to site-specific design.

DEVELOPING BUILDING ENVELOPES WITH DESIGN FOR ADDITIVE MANUFACTURING

Politecnico di Torino, Department of Energy (DENERG) + Department and Architecture and Design (DAD)
Juan Diego Vargas, Stefano Fantucci, Valentina Serra, Guido Callegari, Valeria Villamil Cardenas

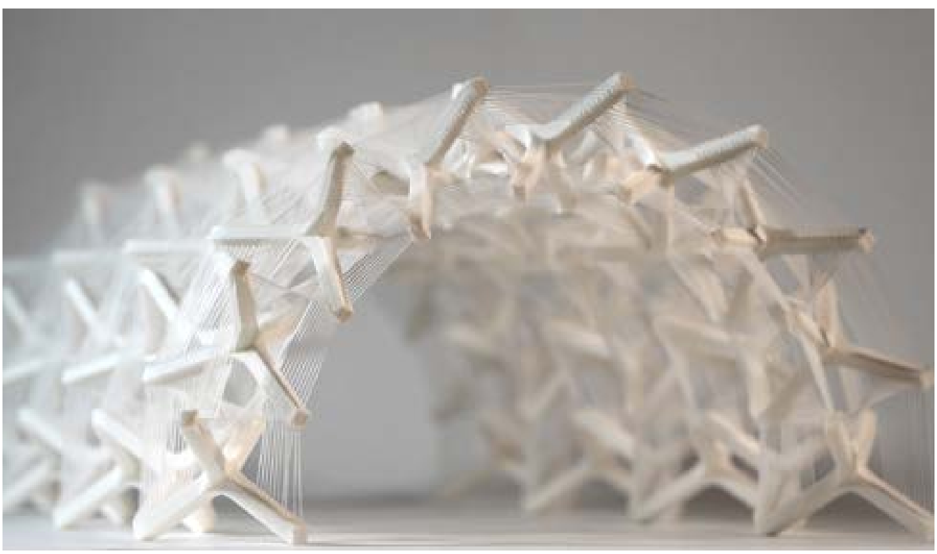
The construction industry is among the largest global energy consumers and contributors to environmental degradation. Within this context, the building envelope plays a key role in determining both energy efficiency and indoor environmental quality (IEQ). Consequently, the development of innovative, high-performance envelopes is essential to addressing these global challenges. This research proposes a DfAM methodology tailored to building envelopes, integrating computational design, performance assessment, and fabrication. The approach leverages additive manufacturing (AM) to produce context-specific façade components featuring mixed cellular infills, combining closed and open porous geometries such as Triply Periodic Minimal Surfaces (TPMS) and conformal lattices. These structures enable multifunctionality, from enhanced thermal insulation to moisture buffering, while also offering architectural freedom for customization. The work introduces WASPer_3DP, an open-source Grasshopper plugin developed for Liquid Deposition Modelling technologies. The plugin streamlines the workflow, from infill design and pores' morphological characterization (like tortuosity) to performance evaluation (like steady state thermal transfer) and G-code generation. It provides designers with flexibility and control by enabling fabrication-informed and performance-based design decisions at the early stages. For this demonstrator, the methodology was applied to fabricate a modular wall prototype, discretized into nine pieces. Each piece integrates a dual-cavity system: an inner cavity, that can be customized for thermal performance and an outer cavity featuring a conformal lattice that adapts its morphology to a non-orthogonal surface, enabling both functional tuning and aesthetic variability. This design illustrates how AM can unlock envelopes that are efficient and that can adapt to diverse climates, contexts, and design intentions.

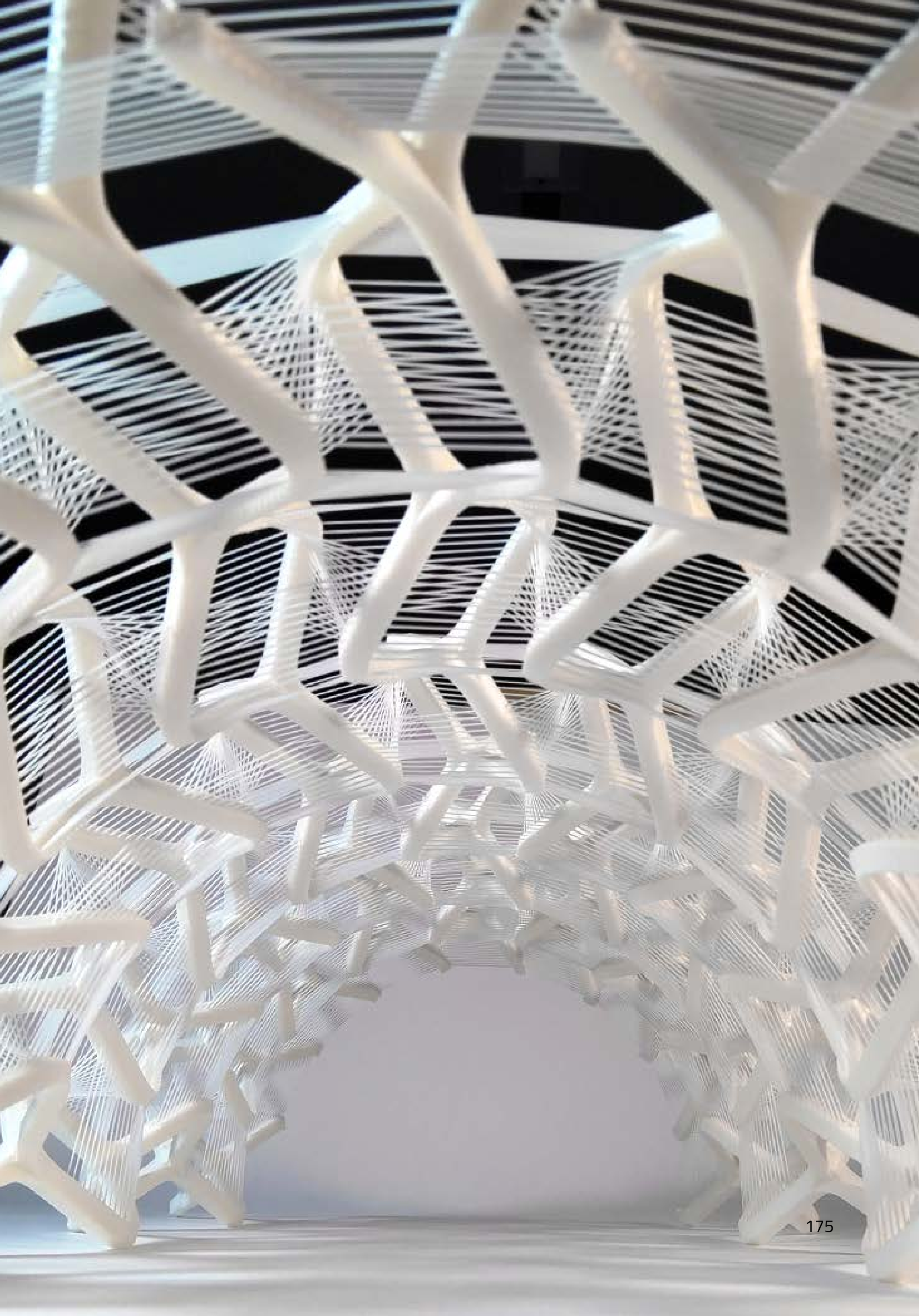


TENSEGRITY SHELL

University of Wuppertal, Faculty of Architecture and Civil Engineering
Alec Singh

Tensegrity is a structural principle in which compression elements do not touch each other but are held in place exclusively by tensioned members (usually cables or strings). The term "tensegrity" – short for tensional integrity – was introduced by Buckminster Fuller in the 1960s. This model explores how a tensegrity-inspired shell can be fabricated using Fused Filament Fabrication (FFF). Conventional tensegrity structures rely on manual assembly, but here the goal was to print the entire geometry in one piece – without additional support material and without post-assembly of members. The larger elements are stabilized only through extremely fine filament strands extruded directly into the air. This printing technique is known as bridging, and it pushes the limits of what FFF can achieve. To enable these filigree connections, the model is printed rotated by 90°, ensuring that all bridging strands run parallel to the build surface. The overall length of the shell is therefore limited only by the vertical build height of the printer. The prototype shown measures approx. 22 × 13 × 35 cm and was produced on a Raise3D Pro2 Plus with a layer height of 0.2 mm. The result is a lightweight, visually delicate structure that demonstrates how digital fabrication can emulate structural ideas usually associated with cables and membranes.

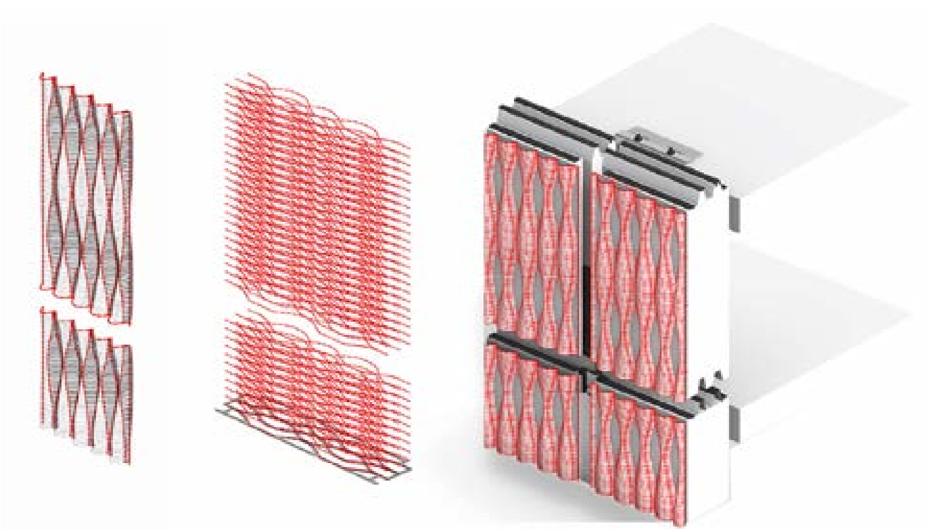




TOWARDS STRUCTURALLY OPTIMISED TOOLPATH STRATEGIES FOR 3D-PRINTED FACADE PANELS

University of the West of England, School of Architecture and Environment
Nzar Naqeshbandi, Francisco Sierra, Tavs Jorgensen, Shwe Soe, Ina Cheibas

This project investigates toolpath planning as a strategy for structural optimisation in 3D-printed façade panels. A digital workflow has been developed that integrates parametric modelling with finite element analysis to generate stress-aligned toolpaths for robotic pellet extrusion. Unlike conventional uniform infill patterns, these toolpaths are guided by principal stress trajectories, embedding structural logic directly into the printing process. The workflow also accounts for fabrication parameters that are critical at architectural scale, including extrusion continuity, layer height, nozzle diameter, inter-path spacing, print speed, and collision avoidance. Coordinating these factors ensures stable material flow, strong interlayer bonding, and dimensional accuracy, allowing computationally generated strategies to be translated into large-scale prototypes. Toolpath optimisation offers significant advantages for construction and façade applications by directly linking structural requirements with fabrication logic. Rather than treating design flexibility as an aesthetic outcome, extrusion paths can be planned to align with performance criteria, enhancing load transfer, reducing material consumption, and improving durability. To demonstrate the approach, prototype façade panels were fabricated using thermoplastic composites, illustrating how stress-informed toolpaths can be validated through physical prototyping and applied to the development of lightweight, durable, and resource-efficient building systems.



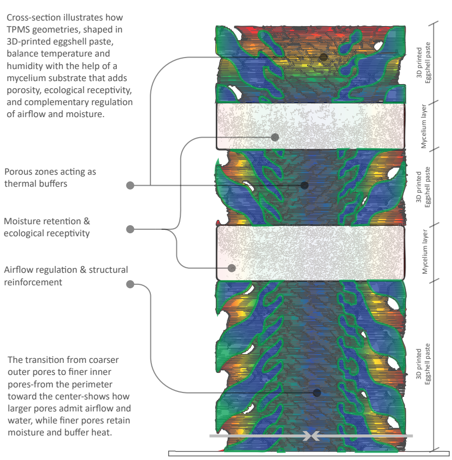
ORGANIC WASTE COLUMNS

Institute for Future Technologies-De Vinci Higher Education & Chair for Biohybrid Architecture-Royal Danish Academy
Hasti V.Goudarzi, Vivien Roussel, Adrien Rigobello, Behnaz Khaksar

Climate change is destabilising insect populations by altering microclimates and degrading refuges, particularly for moisture- and shade-dependent decomposers. In response, this paper introduces a multiscale design framework for 3D-printed insect habitats, developed through a Research-through-Design approach. The framework employs triply periodic minimal surfaces (TPMS) to generate porous, multi-scale geometries from local organic waste, combining a mycelium-infused wood substrate with an extrudable eggshell-based paste. The two materials bring complementary functions: the mycelium substrate provides porosity and ecological receptivity, while the eggshell paste reinforces geometries, regulates airflow, and retains moisture.

Unlike smooth or low-complexity structures, TPMS topologies establish gradients of pore sizes and edge conditions that act as thermal buffers, moisture refuges, and temporary shelters for woodlice, millipedes, springtails, mites, and snails. Habitat logic follows ecological strategies, orienting coarse pores outward to admit water, converging finer pores inward to retain it; scaling cavities to species; and tuning wall thickness to balance shading, airflow, and structural stability. Importantly, the juxtaposition of acidic mycelium and alkaline eggshell introduces subtle pH gradients that invite different microbial communities and organisms, composing niches through both structural and chemical heterogeneity. Alternating layers of the two materials form organic waste columns that dissipate heat, regulate internal microclimates, and retain humidity, while TPMS geometries amplify the surface-to-volume ratio to enhance aeration and colonisation. Evaluation will employ infrared thermography, humidity sensors at multiple depths, and 4–6-week outdoor trials benchmarked against smooth and honeycomb controls. This geometry-first, waste-driven framework demonstrates how speculative design can prototype ecological infrastructures for more-than-human resilience.

Speculative TPMS Temperature Gradient & Habitat Section






COWAVE

Aga Blonska Studio
Aga Blonska

CoWave explores a new intersection of emotion, technology, and sustainability within design practice. The project begins with the recognition that many products are discarded prematurely due to a lack of emotional attachment. CoWave addresses this issue by positioning emotional resonance as a key driver of sustainable design. Using neurodesign methodologies, individual brainwave patterns (EEG data) are captured to reflect emotional responses to shapes, colours, and materials. This data is then processed by AI-driven generative algorithms to create hyper-personalised forms that embody each user's unique emotional imprint, fostering deeper attachment and extending product lifespan. By merging neuroscience, artificial intelligence, and additive manufacturing, CoWave unites emotional intelligence with environmental responsibility. The project's bespoke acoustic panels are fabricated from recycled materials such as wood dust, plastic waste, and coffee grounds, and can be fully reprocessed and reprinted, ensuring a closed-loop material cycle. This integration of emotional data and circular production demonstrates how neurodesign can lead to emotionally meaningful, sustainable objects. CoWave thus proposes a new paradigm in design – one rooted not in consumption and disposability, but in emotional connection, care, and enduring value.

HYBRID SLAB

University of Minho, School of Architecture, Art and Design
João Carvalho, Bruno Figueiredo, Paulo J. S. Cruz

The Hybrid Slab introduces a hybrid flooring system that integrates 3D-printed ceramic components with wooden structural elements. The ceramic vaults, developed with geometries optimized for structural performance and material efficiency, rest on longitudinal wooden beams, replicating the behavior of conventional lightweight slab systems. A 5 mm cork layer is placed over the ceramic elements to distribute loads and enhance the overall stability of the assembly. Wooden boards are then screwed onto the beams and receive the final flooring finish. The system also allows for the incorporation of post-tensioning elements within the beams, increasing structural capacity without significantly altering the slab's volume. The 3D printing of ceramic components enables the customization of forms and streamlines the production process, combining traditional techniques with modern technology. The Hybrid Slab offers a sustainable, lightweight, and high-performance construction solution.

MURALIS

University of Florence, Department of Architecture
Elisa Mazzoni, Michela Turrin, Rosa Romano

Muralis is the outcome of an international research project conducted by the University of Florence and Delft University of Technology within the R3NEW doctoral program. It consists of a multi-performance clay façade component fabricated through 3D printing, designed to maximise the integration of Cymbalaria muralis, a stress-resistant plant that naturally grows on brick walls in Mediterranean urban contexts. The research addresses the growing environmental stresses in contemporary cities, manifested in phenomena such as the urban heat island effect and the decline of biodiversity: critical ecological imbalances with significant consequences for human and non-human well-being. At the same time, the project aligns with circularity and sustainability standards promoted by European and national frameworks in the building sector (EPBD; European Green Deal; Renovation Wave). The systemic complexity of these dynamics requires a rethinking of conventional architectural processes. Accordingly, the study adopted an interdisciplinary approach, engaging biologists and employing biodiversity-inclusive parametric analysis and design methods, alongside multi-performance optimisation of the façade component. This process reinterprets clay - a natural, and traditional building material - through advanced digital manufacturing techniques. In Muralis, no element is purely aesthetic: biological, architectural, and fabrication requirements are translated into geometric forms that ensure multiple performances and functions. This façade product addresses the potential of a bio-inclusive approach that integrates 3D printing and vegetation affordances. It constitutes a concept prototype of a technological, biophilic, and low-impact Nature-based Solution, towards scalable applications contributing to carbon reduction, ecological resilience, and restorative architectural practices in line with international sustainability goals.

SMART METAL ADDITIVE LIGHT JOINTS: WAAM AND LASER-BASED REVERSIBLE CONNECTIONS FOR THIN-WALLED STEEL CONSTRUCTIONS

Politecnico di Milano, DABC
Ornella Iuorio, Ehsan Bakhshivand, Alireza Bagheri, Barbara Previtali

Metal additive manufacturing was first proposed at the beginning of the XX century, but has only recently entered the construction market. This work has investigated the opportunity to adopt metal printing for the development of novel metal additively manufactured connections designed for lightweight steel systems, to enable the assembly and disassembly of cold-formed steel housing. Beyond the well-known advantages of additive manufacturing, this hybrid connections, novel both in design and in its combined realization methods, were conceived from the very beginning to fully explore the potential of these technologies in the construction sector. Focus of our work has been on overcoming the challenges of printing on thin substrates, such as 1 to 1,5 mm thick cold formed steel sections, which characterize cold formed steel housing structural typologies. Printing on such slender sections requires precise control of metal printing parameters to prevent distortion, and residual stress accumulation. To address these challenges two metal printing methodologies, among those belonging to Directed Energy Deposition (DED) methods, have been employed: Wire Arc Additive Manufacturing (WAAM) and Laser Metal Deposition (LMD). The opportunity to develop intricate geometries with these metal processes provided the opportunity to propose a novel, fastener free, connection between studs and joists of cold formed steel systems, that could not be realized with traditional construction methods. Specifically, two connection systems, named Gear-Wheel (GW) and Key-Wheel (KW) connections have been developed. The GW connection (shown in Figs. 1 and 2) is composed of an interlocking mechanism, with a male, female connectors respectively printed on the studs and joists, while the KW connection features one printed wheel on the stud and a laser cutter counter part on the joist. This creates an interlocking connection that resists shear forces and bending moment through the bearing of the surfaces. The result is a novel system that advances automation in construction industry while responding to the principles of circular constructions.

BAROQUE GLITCH

Florida Atlantic University, School of Architecture
Dustin White

Baroque Glitch presents a fragment – a singular architectural component extracted from a speculative, larger assembly, designed as both threshold and artifact. Acting as a portal, the object invites movement around and through it, blurring the boundary between façade and structure, surface and mass. It draws from the perspectival and theatrical strategies of Baroque architecture, specifically the way ornament and geometry were used to choreograph experience and spatial perception. Digitally 3D-printed by Concr3de from stone using stereotomic logic, the piece operates as a warped structural panel, shaped to exaggerate depth, curvature, and shadow. Its form recalls Borromini's undulating facades, but here it is distilled into a solitary, self-supporting module that expresses both architectural memory and digital transformation. Wrapping seamlessly across both faces of the portal is a generative surface inlay: an AI-assisted reinterpretation of Baroque ornamentation. Rather than applied decoration, this inlay is integrated into the geometry of the block, flowing continuously from one side to the other. It evokes historical scrollwork, grotesques, and Rocaille forms—but recomposed as synthetic pattern, low-res filigree, or glitched relief. The motif distorts across the surface as the viewer moves around the object, creating a visual tension between memory and mutation, tradition and machine hallucination. Baroque Glitch explores how ornament can embed itself within structure, and how stone—when filtered through computation – can act not only as tectonic matter but as an experiential device. It asks the viewer to circle, pause, and perceive, engaging both the object and their own shifting perspective.

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