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Integrated Design Strategies for Multi-scalar Biopolymer Robotic 3D Printing

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1 Demonstrator wall showcasing an assembly of forty-four 3D printed biopolymer components

ABSTRACT

Additive manufacturing technologies have the potential to initiate changes in architecture's material culture and move us towards a bio-based paradigm. Robotic 3D printing can propose new design languages, logics and tectonics specific to wet biopolymers. In this paper we present strategies and workflows for cellulose-based biopolymer 3D printing. We propose a digital design framework informed by the fabrication system and guided through human design input. The workflow stabilizes the material at the scale of the toolpath, the component, and the wall assembly, by integrating joinery and cross-bracing together with the component geometry. We showcase the feasibility of a large-scale dry-assembly of 3D printed biopolymer components. The demonstrator wall allows us to evaluate our workflows and discuss the challenges and implication of bringing biomaterials in our built environment.

INTRODUCTION

Rising awareness of architecture and construction's impact on the climate crisis through carbon pollution and material overconsumption (Allen et al. 2014) pushes us towards a fundamental rethinking of the way we design and produce our physical spaces. Not only should we rethink our building systems, but also the design logics that feed into them, and the material practices that underpin them. This implies a radical re-evaluation of the way we understand architecture, its production, and its objective. Decades of research into restorative and regenerative design principles have led to new political frameworks of operation such as the European Green Deal (European Commission, Directorate General for Research and Innovation 2021) and other green initiatives. A new model for material consumption would entail shifting away from the threatened and finite materials of the geosphere, and towards the abundant and cyclical materials of the biosphere. This bio-based agenda is building momentum in architecture and design, with attention placed on timber glulam construction, bamboo and rattan, natural fibers, and an emerging class of bio-polymer composites (Hebel and Heisel 2017). This allows us not only to build in a bio-integrated manner, but also to think about our built environment as a carbon sink (King 2017).

Pragmatically, there is a marked knowledge gap curbing this transition. On the one hand, the contemporary construction industry, its supply chains, design workflows and construction systems, are designed for materials that are static, firm, homogenous, and stable. This relies on centuries of accrued knowledge and efforts to standardize material behavior and durability through certified industrial fabrication processes. On the other hand, working with bio-based materials requires a fundamentally different paradigm for they are shaped by growth cycles, and so are characterized by heterogeneity and anisotropy (Pradhan et al. 2021). They are furthermore dynamic as they age (such as in creep), degrade, and respond to environmental triggers such as temperature and humidity (swelling and shrinking). Advances in computational design can close this gap by proposing new data-rich design workflows and smart fabrication pipelines that can account for and work with the complexity of bio-based materials (Thomsen and Tamke 2022). The goal of this research is to propose ways where bio-materials can interface and complement existing built environment in novel hybrid ways.

In this paper we present strategies and workflows for cellulose-based biopolymer 3D printing. Through the production of design prototypes and a full-scale demonstrator, we explore how 3D printing can be instrumentalized to propose new applications of bio-based materials in architecture. Cellulose is the most abundant organic compound on Earth (Pattinson and Hart 2017). However, biopolymers are unruly materials; they are less stable and less durable than their petrochemical equivalents (Nagalakshmaiah et al. 2019). Rather than operating within a schema of material conservation by optimizing design for minimal material usage, strength, and durability, working within a bio-based material paradigm asks us to shift our design logics to embrace a new architectural language defined by shorter life spans, heterogenous properties and emerging design aesthetics. The demonstrator presented in this paper is an experiment allowing us to create and test an interior bio-printed element, whose lifespan and performance is impacted by slow temperature and humidity fluxes within an inhabited environment, while protected from more aggressive degradation processes such as precipitation and UV. We report on various experiments that explore methods of material stabilization, at the intersecting scales of the toolpath, the component, and the wall assembly. We combine geometric design aspects and parametric workflows with fabrication and material system constraints to bring an unruly material into architectural tolerance through a new digital tectonic expression specific to digitally designed, robotically-produced biopolymer prints.

BACKGROUND

Curing of Large-scale Robotic 3D Prints

Large-scale robotic 3D printing has been gaining ground in architectural research and industry. Differently from small-scale rapid prototyping applications which usually involve high resolution slicing, and dense infills with aim to reproduce the element at high fidelity (Chua and Leong 2014), 3D printing at large scale entails a deeper understanding of the material system. On the one hand, efforts are made to tune the extruder system to the specific material that is being extruded, and on the other hand, the printed material's composition and physical properties are tuned for best extrusion flow and print stability. Large scale concrete 3D printing for instance requires specific mixes rich in plasticizer to prevent buckling during the print, and a designed pumping system for flow regulation from mixer to extruder (Gosselin et al. 2016). Similar to cast concrete, the curing of the print is a chemically induced exothermic reaction lasting several weeks. This allows to print dense prints with very thick beads. In the case of large-scale plastic 3D printing, the curing is immediate as the material flows outside of the extruder nozzle thanks to the usage of fans that cool the material below its liquid flow point. This allows to create both sliced surfaces (Schork et al. 2021) as well as spatial trusses (Soler, Retsin, and Garcia 2017). In these material systems, the curing is independent of the geometry of the print. This is not the case with 3D printing of natural materials, such as earth, clay, or bio-composites. Here, the materials undergo a two stage fabrication process: an initial rapid forming followed by a slower evaporative hardening phase.

Most bio-based extrudable materials are water-based slurries. During the slow and long curing phase, the water content will evaporate and allow the print to dry and gain strength. Water, although problem causing, is a necessary component in the mix, as it allows to reach an extrudable viscosity (Campos, Cruz, and Figueiredo 2020; Rossi et al. 2022a). Therefore, geometric strategies for toolpath design and curing control become a crucial aspect of biomaterial 3D printing. In current work, localized curing control is commonly implemented through fans. In the "Ocean Pavilion" project (Mogas-Soldevila et al. 2015), the material is printed as a thin flat sheet, topped by a computer-controlled evaporation system, composed of one hundred fans, which precisely controls the hydration through computerization and drives the self-folding behavior of the sheet. Alternatively, for smaller scale prints, the fan grid is positioned on the extruder itself, thus concurrently stabilizing the ongoing print and initiating the curing process (Dritsas, Hoo, and Fernan 2022). Toolpath control and strategic digital design is particularly present in clay and earth printing, where the mass of the printed elements is too large to be influenced by fans. For example, wall sections have been specifically designed with vertical ventilation shafts for evaporative cooling performance of the building (Chronis et al. 2017). These shafts, while designed for the usage phase of the wall, also contribute to the curing phase, promoting an equal drying of the wall which prevents shear cracking and failures. With biopolymers and bio-receptive composite 3D printing we see two tendencies. The first is to use parametric spatial lattices that offer possibilities for lightweight aerated porous panels to be tiled and attached to a substructure (Chiujdea and Nicholas 2020). The second is the usage of space filling curves (Dristas et al. 2020) or reaction diffusion algorithms (Goidea, Floudas, and Andréen 2020) to generate layered column structures. Both strategies allow to maximize the surface to volume ratio, which promotes ventilation during the evaporative drying.

While these presented projects constitute pioneering efforts in the field of biopolymer 3D printing, the results showcase examples of standalone monolithic objects, with a simple stackable assembly. This lack of consideration for dry assembly joint solutions for 3D printed elements exists across multiple efforts within the large-scale 3D printing community. Here, the difficulty in printing overhangs and interlocking geometries with acceptable tolerances are seen as key limitation of the fabrication process (Shaker et al. 2021). Our research goes beyond state-of-the-art by extending considerations of standard assembly and joinery prevalent in timber construction to 3D printed biopolymer elements. This is achieved through the design decision to rotate our non-standard components 90 degrees with respect to the print bed. In this way, we work with the width and breadth of the print rather than its thickness. Furthermore, we are able to harness the structural capacities of the bead-oriented fibers that are embedded in the material. This introduces biopolymers to the territory of prefabricated, transportable, and maneuverable large-scale assemblies. Our proposal of a wall assembly demonstrator alludes to possibilities of using these printed biomaterials as retrofitting systems that interact with, and improve qualities of existing built environment—a matter of high priority in the EU context (Uihlein and Eder 2010).

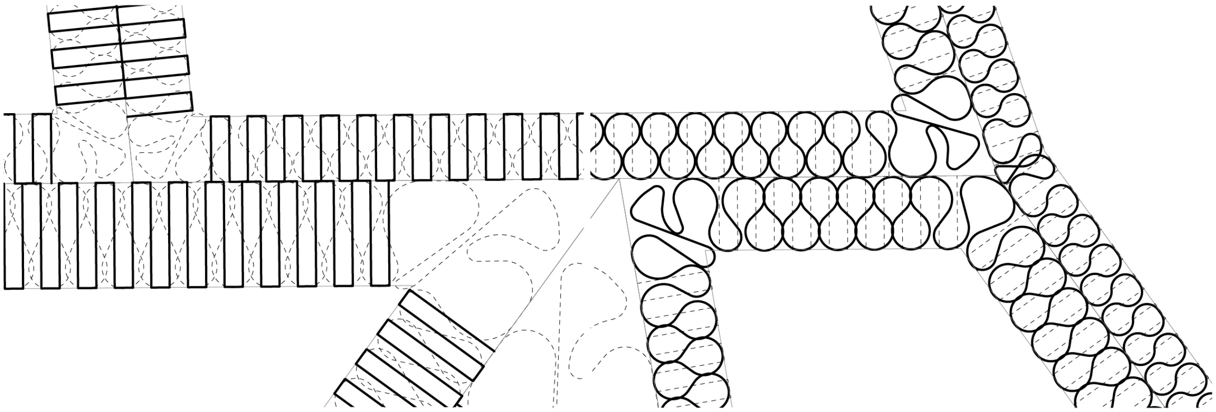
MULTI-SCALAR METHODS FOR STRUCTURALLY STABLE BIOMATERIAL 3D PRINTS

In this research we explore the 3D printing of a cellulose-based biopolymer slurry, and we present associated design strategies and fabrication workflows. Our approaches suggest a shift in design logics to embrace the abundance and heterogeneity of biomaterials and develop novel design aesthetics and program potentials for them. Our material recipe is developed in-house (Rech et al. 2021). It blends cellulose flock, wood flour, glycerol, xanthan gum, calcium chloride, and water at 72% of the total weight ratio. This water evaporates during a 15-day post-printing period enabling the material to harden and gain strength, but also causing the material to shrink. To best understand the unruliness of our material and be able to bring it to architectural scale, we develop a Material Monitoring Framework to study its behavior. Our results (Rossi et al. 2022a) showcase that geometry as the critical driver for surface evaporation. Our findings showed that open geometries, which expose more surface area to airflow, dry more evenly, while denser geometries are more prone to warpage. This became a driving consideration for the design of the demonstrator components.

In this paper we focus on design tools, strategies, and potentials of 3D printing large scale biomaterial assemblies. We have developed an interactive parametric model that generates print toolpaths integrating structural and assembly features into the design language of the components, based on designer input. The model ensures material stabilization at the scale of the toolpath, the component, and the wall assembly. The model combines geometric design aspects with fabrication understandings and material system constraints to bring an unruly material into architectural tolerance. We detail various aspects of the model across increasing scales.

Print Stability: The Loop

One of the main challenges of printing with wet materials is that they should be able to bear their own weight during the printing process, therefore avoiding buckling and print failure. In the concrete 3D printing industry, this problem is solved with the addition of plasticizers, thick print beads, multiple shells, and print delays. We seek a geometrical solution to the



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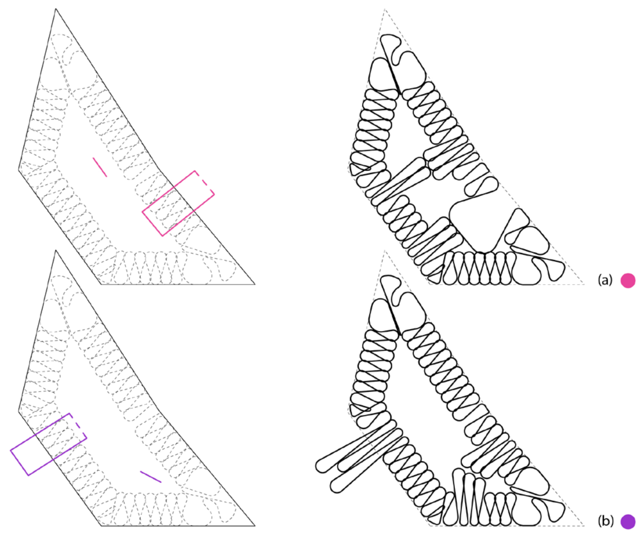
problem since our recipe is to be maintained 100% organic and biodegradable, and thicker beads or multiple shells would impede the proper drying of the print (this would cause the formation of a crust, and rot in the center). Curvature-induced stabilization is achieved through a half circular toolpath we term "The Loop." The Loop allows us to gain cross-sectional moment of inertia without compromising the aeration and ventilation. The sizing of the loops is informed by the fabrication setup. The algorithm (Figure 2) operates on the basis of the print nozzle size, which informs both the base subdivision parameter (1.5x the nozzle diameter) as well as the overlapping parameter (0.5x the nozzle diameter). Since our material is fiber-oriented, the correct overlap parameter is crucial to ensure aeration without delamination.

Component Stability: Cross Bracings and Joints

While the sizing of the loops is informed by the fabrication setup, their depth is informed by the load to which the component is subjected. Our algorithm uses a simple load approximation given by the specific weight of the material and the gravity and self-weight load network. The higher the load, the thicker the cross-sectional frame of the component. The algorithm operates using a data tree structure which allows to add extra features to selected edges without having to manually manipulate the loops, which would be cumbersome. Instead, the algorithm searches for affected edges based on the manual designer guideline input, manipulates the underlying polyline, and replaces the edge branch in the data tree. This method allows us to add different features sequentially using the same integrated loop language, in a simple plug-and-play flexible method: cross bracings, edge thickeners, in-plane joints, and transversal joints (Figure 3). For example, to generate cross bracings that guarantee the stability of the cross-sectional frame against torsion, the designer draws a simple line within the component, the algorithm finds the affected parallel edges, pulls the closest perpendicular loops to the drawn bracing ridge line, and regenerates the edge. For in-plane joints, a similar search is conducted. The designer draws a rectangle on the common edge between two components where the joint should be hosted, using the connectivity graph; the male and female components are identified, and a protruding male joint is generated by pulling the loops, whereas an accommodating female joint is generated by deleting the loops. Inner corners of the components



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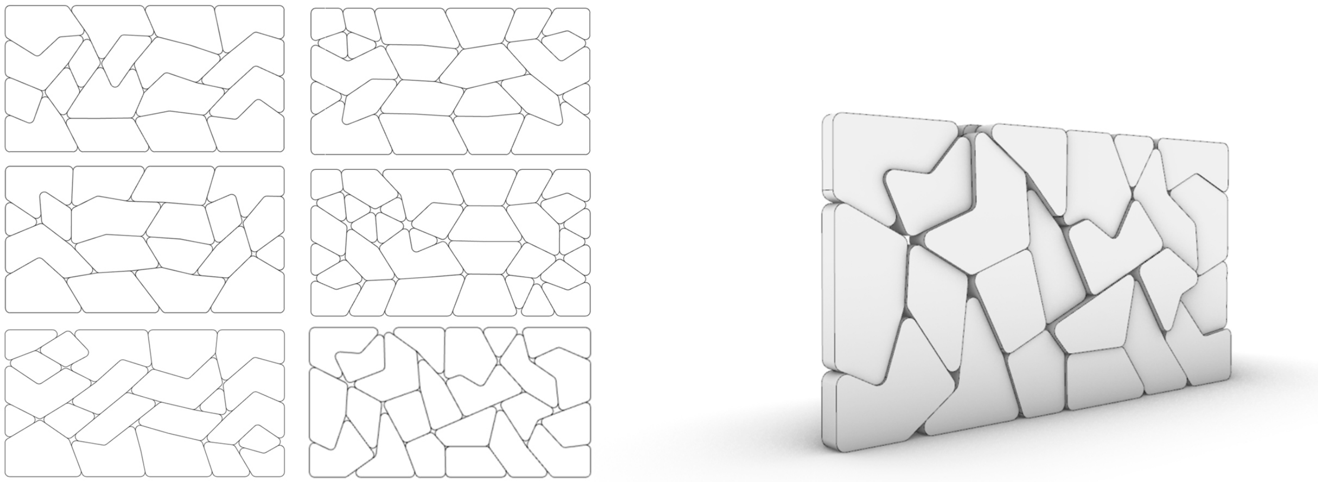
2 Loop generation algorithm: (a) A polyline is generated between the original outline and the offset outline. The spacing is informed by the fabrication parameters, and the polyline is then expanded, manipulated during the design process, and the curved printing toolpath (b) is generated in the final stage.

3 Example of designer input on the base loop (left) and integrated component design with joints and cross-bracings (right). The cross bracings are informed by little dashes that pull together the affected edge loops, while the joints are defined by rectangles reaching between the neighboring components. The dashed edge points to the male side of the joint: in (a) it falls outside the component, and therefore, a female joint is generated, and in (b) it falls inside the component and a male joint is generated.



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are reinforced using a tripartite loop, as preliminary tests have showed that they constitute a weak point in the component if left without reinforcement.

Structure Stability: Macro-scale Assembly

The algorithm operates with an input of component outline. From our structural characterization testing, we know that it behaves better in compression than in tension (with a density of 527.06 kg/m3, and an approximately 140 MPa modulus). To ensure cyclopean compression-based stacking, we therefore, design a tessellation system based on a triangular module. The components are generated using an agent-based system that takes into consideration geometrical constraints that stem from the fabrication system, for instance, component maximum and minimum area, maximum and minimum length of edge and angle with neighboring edge, and maximum and minimum number of edges per components. The resulting tessellations (Figure 4) are evaluated based on the load network explained above. Discontinuities in the load path inform where the in-plane dovetail joints should be located. Finally, the assemblies are tapered in thickness towards the top of the structure.

EXPERIMENTS AND RESULTS

Multi-material Prints

Our recipe has the capacity to change its properties by varying the fiber used. We have so far experimented with replacing the cellulose paper flock with linen fibers, cotton fibers, ground bark, and seagrass. Each different fiber lends the mix not only different properties in term of color and texture, but also structural performance. This opens the possibilities for multi-material prints where the recipe is topologically graded to respond to functional criteria. Figure 5 shows two multi-material prints where the two material beads have been printed adjacently and, through the shrinkage that occurs while drying, have been fused into each other.

Multi-scalar Prints

Our developed toolpathing algorithm can be adapted to print at multiple scales since it is nozzle-size based. Our material presents viscosities that are compatible with cement extrusion hardware. For the printing of the small-scale prototypes, we have used an ABB1600 robot, a custom in-house end-effector extruder fitted with a 6 mm nozzle and an auger screw for flow stabilization, fed with a pressurized 10 L acrylic tube at 2.5 bar. For the printing of the wall demonstrator components, we used the same extruder fitted with a 11 mm nozzle and fed by a Mai 2Pump Pictor. Further experiments are currently being carried out for large-scale components using a concrete 3D printing gantry system fitted with 30 mm extruder nozzle (Figure 6).

Demonstrator Wall

As a proof of concept of internal partitions made of 3D printed cellulose components, we have fabricated a wall assembly spanning 3 meters long by 1 meter wide by 1.8 meters tall (Figures 1, 7). It is composed of 44 polygonal components and tests a corner configuration through a T-shaped composition. The connection between the two orthogonal elements is achieved using a dovetail joint. The joint pieces are printed with staggered heights to ensure three dimensional interlocking. The components are rotated 90 degrees with respect to the print bed. This allows the fiber orientation embedded in the print bead to be used for structural performance. The roughness between the component outlines and the friction within the male/female joint hold the structure standing. This

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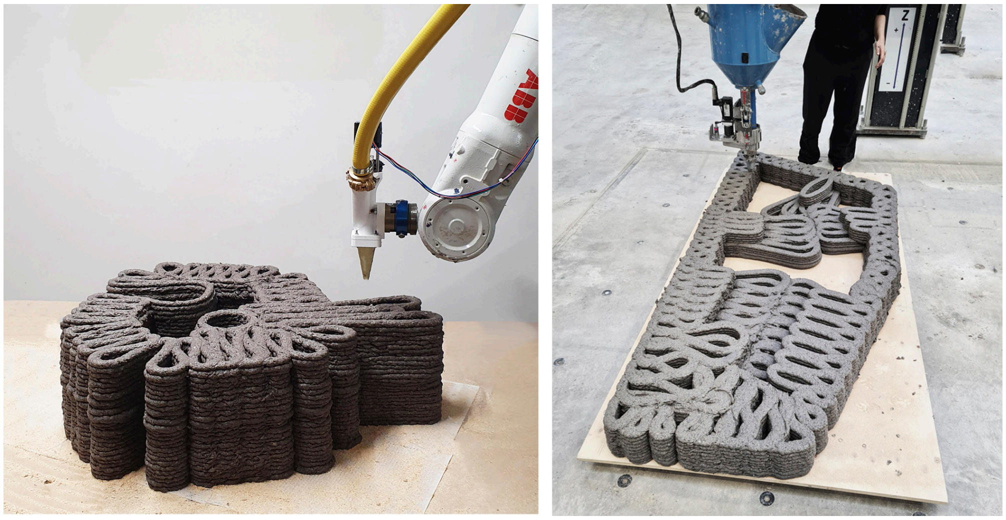

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4 (left) Tessellation iterations produced by the agent-based algorithm; (right) final tessellation volumetrically staggered

5 Examples of multi-material prints using different fibers: cellulose flock (gray), cotton (blue), and bark (brown). Different techniques are tested: interlayer material switch, and side-to-side bead switch

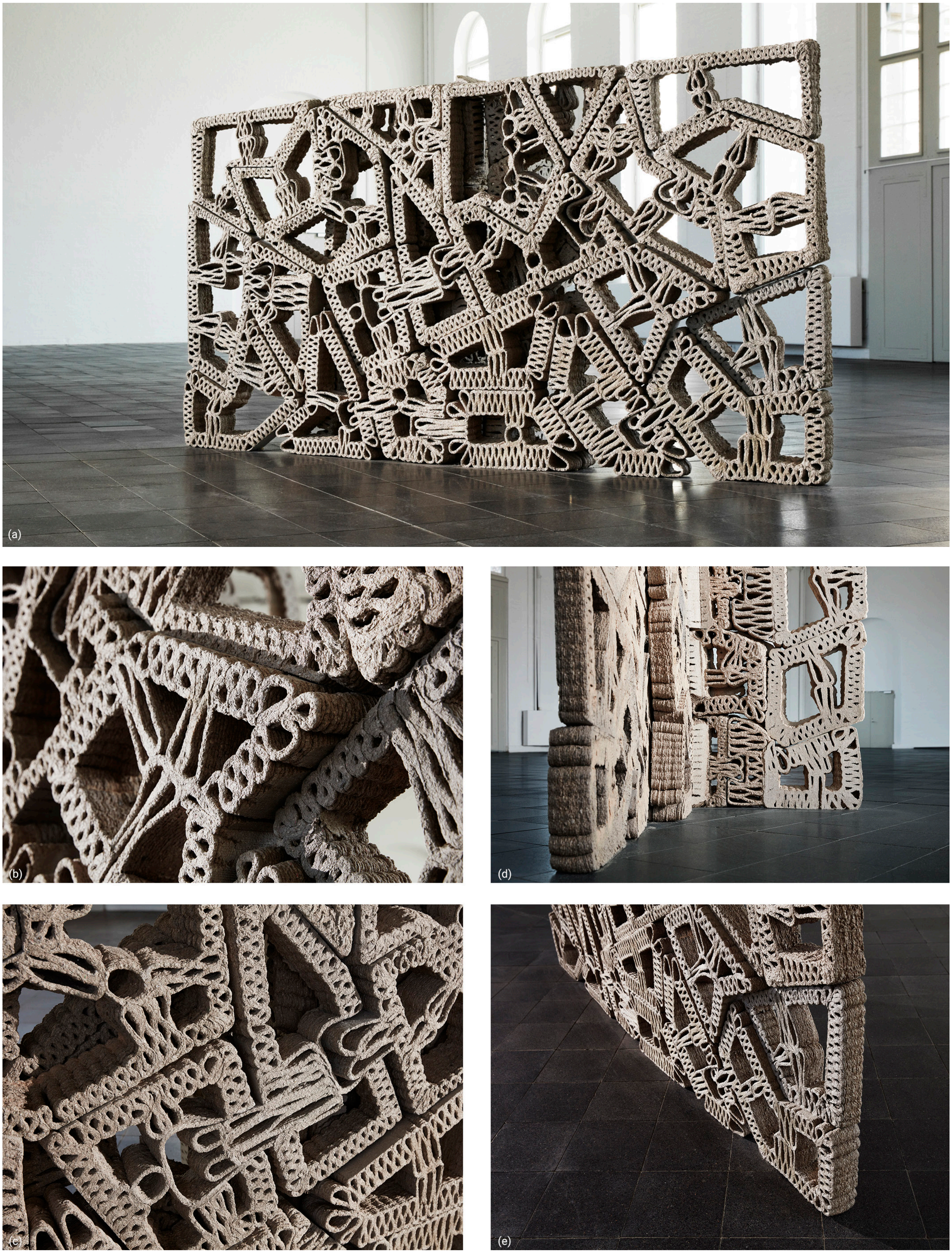
6 (left) Demonstrator component print in our robot lab with a 40 x 40 cm area; (right) scaled up component printed on the gantry system spanning 200 x 90 cm

shows that prefabricated biopolymer components can be integrated together using dry assembly, which can be further stabilized with mechanical fixings if needed. The components express a new tectonic language that integrates frames, bracings, and joints. It explores notions of opacity across the wall. The components are light-weight, and the wall can be assembled by two people in one hour.

DISCUSSION

The demonstrator wall is a successful example showcasing the feasibility of a large-scale dry-assembly of 3D printed biopolymer components. The research points to a series of key considerations in working with biopolymer composites. In scaling up from small probes and prototypes to the demonstrator, substantial performance and fabrication driven changes challenge the design workflow. Firstly, some challenges are due to production and drying logistics. For instance, while the hopper pump allows us to print without a capped volume limit, material must be constantly prepared and fed to it. Using an industrial bread mixer allows us to mix 10 L batches at a time, yet a print in the wall uses an average of 25 L of material. Material can be prepared a few days in advance, but it must be stored in airtight bags, and we have found that mixing material batches of different ages in the same print can cause problems in print consistency. Moreover, the prints must be moved from the print bed to the curing rack while wet; this is when they are most fragile and prone to buckling, and also most heavy. In order to mitigate this, we designed a stretcher system allowing for their transport by two operators. The curing room must be kept at high temperature (27 degrees) and low humidity (35-40%) and be fitted with fans to ensure constant airflow and quick extraction of the water from the material. This process can be quite lengthy; we have found that the densest components (the bottom row of the demonstrator) required 3-4 weeks of drying time, while the lightest pieces (the top row of the demonstrator) were cured within 7-10 days. We have also found that loading the components before they are completely dry can cause delamination and failure.

Secondly, other challenges are inherent to the material system itself. We are aware that as the material dries and loses water, the geometry shrinks. This shrinkage has been considered by calibrating the oversizing of the printed components so that the dried geometry interlocked together. However, we have found that while the tolerances on the component outlines were sufficient for fitting, the orthogonality of the component edges and the tolerance around the interlocking joints was challenged. Here we found that the taller the component is, the higher are the chances of the beads in their wet state to buckle under their own weight and bulge out of plane. This constituted a problem given the need to rotate our component and stack them against each other's planar edges. As



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7 (a) Frontal view of the demonstrator wall; (b, c) detail shots of the components cross-bracings and joints; (d) rear view of the corner solution; (e) textured side edge of the wall

8 (left) Joint refining using a hand-held jigsaw; (right) two interlocking pieces fit together through an in-plane joint and subsequently placed in the interlocking assembly

our material can be easily post-processed with standard woodworking tools (Figure 8), this print artifice could be easily corrected, and our assembly logic remained valid. To track these deformations, we have monitored the components during their curing using an Opti-Track setup and have compiled a dataset to train a machine learning algorithm for warpage mitigation. We developed methods for geometric data encoding, tolerance-informed data augmentation and statistical modeling, which are reported in Rossi et al. 2022b.

CONCLUSIONS

In this paper we have presented integrated design and fabrication strategies for multi-scalar biopolymer robotic 3D printing that are showcased through the production of a room-scale demonstrator composed of dry-assembled cellulose biopolymer components. The proposed digital workflows are informed by the fabrication system and are guided through human design input. The outcomes bring together joinery and cross bracing in an integrated aesthetic and tectonic logic that is more suited to design with unruly biomaterials than to 3D printing.

From a broader perspective, this project has allowed us to demonstrate the possibility of printing and drying larger cellulose components that is enabled by the geometrical strategy we have adopted and that maintains both structure and aeration in the components. Both the scale of the elements and the reversibility of the dry assembly are compatible with a retrofitting architectural paradigm and allow for a responsive maintenance regime and replacement of parts. The ability of the elements to carry a load equivalent to that of an interior wall reinforce this potential. Immediate realizations are that these biomaterials have the potential to regulate occupancy, humidity, and sound, and thus to improve the quality of existing built space. We will explore these aspects in future work.

In future work, we will also examine the improvement of the tolerance control of the components from wet to dry. The research presented here runs in parallel with a machine learning track that investigates how to predict the deformation of the original print during drying and ultimately to inform the design of objects made from biopolymers. Here, our goal is to differentiate the tolerance control around the joint and edges. Furthermore, we plan to expand the 3D printing process to non-flat printing beds using conformal techniques.

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IMAGE CREDITS

Figure 1, 7: Anders Ingvarsten ©CITA / Royal Danish Academy, 2022
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Figure 4: Ruxandra Chiujdea ©CITA / Royal Danish Academy, 2022

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