D3.1 Parametric design workflow

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Executive Summary

Deliverable 3.1 "*Parametric design workflow*" presents the development of a computational design framework that focuses on the process of parametric design, modelling, and robotic fabrication of multifunctional architectural components. Specifically, this report outlines a step-by-step workflow that integrates the parametric design of architectural typologies with robotic additive fabrication processes. Exploratory parametric design studies are carried out to identify potential architectural typologies based on the known behaviour of biofoam material. Drawing on its lightweight, porous character alongside its thermal and acoustic properties, proposed architectural applications include adaptive façade systems, self-shaping insulation and acoustic wall panels, as well as shading canopies. Parametric 3D models are created using a visual programming application running within an industry standard design environment to investigate the design opportunities for these applications. In parallel, a robotic additive design-to-fabrication workflow is developed within the same computational environment to enable the translation of parametric design models into additive manufacturing toolpaths and machine-readable code. This deliverable serves as a foundational component of the ARCHIBIOFOAM project by bridging material-informed design with digital fabrication workflows. The architectural typologies identified in this report will serve as case studies for the subsequent evaluation of the design software to be developed in future tasks.

Acronyms

Acronym	Meaning
AEC	Architecture, Engineering, Construction
CAD	Computer-Aided Design
ICD	Institute for Computational Design and Construction
HVAC	heating, ventilation, and air-conditioning
RH	relative humidity
SRC	Source File
UMIL	University of Milan

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1. Introduction

1.1. Project Overview

The Architecture, Engineering, and Construction (AEC) industry accounts for nearly 40% of annual global greenhouse gas emissions [1]. A significant portion of these emissions arises from the production of conventional building materials such as steel, concrete, and glass [2]. Beyond material production, contemporary building designs rely heavily on heating, ventilation, and air-conditioning (HVAC) systems to maintain occupant comfort, leading to significant energy consumption throughout a building's operational lifespan [3]. Furthermore, the end-of-life phase of conventional building materials poses an enduring sustainability challenge, with more than 50% of construction and demolition waste remaining unrecycled [4]. Collectively, these challenges underscore the urgent need for research into innovative architectural strategies and sustainable material systems that can substantially reduce the environmental impact across the entire lifecycle of buildings.

The ARCHIBIOFOAM project aims to address these challenges by developing mono-material yet multifunctional material systems for architecture. Through the integration of bio-based materials, computational metamaterial design, and robotic additive manufacturing, the project seeks to replace high-embodied-energy materials with a novel biofoam system that can be functionalised to meet multiple performance requirements, thereby eliminating the reliance on multi-material layered construction. By bridging material innovation with digital manufacturing, the project aims to establish a new paradigm in fabrication for the AEC sector, unlocking material and performance potentials that remain unattainable through current additive manufacturing technologies.

1.2. Computational Design and Digital Fabrication in Architecture

Computational design has become a central paradigm in contemporary architecture, reshaping the ways in which buildings are conceived, designed, and constructed. While Computer-Aided Design (CAD) primarily digitises manual drawing and modelling processes, computational design extends beyond representation by generating design solutions through responsive, data-informed workflows [5]. Unlike traditional approaches to form-making, it emphasises the generative process, integrating material performance alongside programmatic, economic, and environmental parameters as operative design and feedback criteria. The integration of computational design with digital fabrication technologies, including multi-scale additive manufacturing and robotic control, further expands the

possibilities for materialisation in architecture. In contrast to conventional subtractive fabrication methods, which generate considerable material waste, additive manufacturing enables greater geometric freedom with high material efficiency. Within the context of this project, these developments establish a foundation for investigating biofoam-based architectural components, aligning computational design methodologies with sustainable material innovation and robotic fabrication processes. In doing so, the project will propose novel architectural typologies that prioritise ecological responsibility and adaptive performance.

1.3. Work Package 3 – Deliverable 3.1: Parametric Design Workflow

The objective of Work Package 3 "*Design for function and fabrication*" is to establish the design and fabrication potentials of a multifunctional biofoam material system for architectural applications. Based on the known properties of the biofoam developed by the project partner Aalto University, this work package aims to develop an integrated design-to-fabrication workflow that supports the production of multifunctional and adaptive architectural elements. In particular, Work Package 3 is structured into two tasks. Task 3.1 focuses on the development of design-to-fabrication workflows for functional and adaptive structures, while Task 3.2 includes a parameter study of functionalities enabled by the biofoam material. Deliverable 3.1 corresponds to Task 3.1 and presents the complete process of parametric design, modelling and robotic additive fabrication for selected architectural typologies. The typologies outlined in this report will serve as case studies for the integration of the optimisation software developed in Work Package 2 by the project partner University of Milan (UMIL), thereby facilitating exploration across a range of design conditions.

2. Computational Design Methodology

The computational design-to-fabrication workflow is developed using a visual programming application within an industry standard design environment. Rhinoceros 3D, commonly known as Rhino, is a CAD software widely used in architecture for its ability to define and manipulate complex geometries. Grasshopper is a visual programming application integrated with Rhino's 3D modelling environment. As illustrated in Figure 1, the platform offers an intuitive interface for parametric and algorithmic design, accessible to both novice and advanced users. In addition, Grasshopper is supported by an extensive library of plugins that add specialised functionalities across a range of domains. These include tools such as structural analysis [6], typology optimisation [7], environmental simulation [8], and robotic control [9]. This flexibility makes Rhino and Grasshopper an accessible yet

powerful platform for integrating design, performance evaluation, and fabrication within a single workflow.

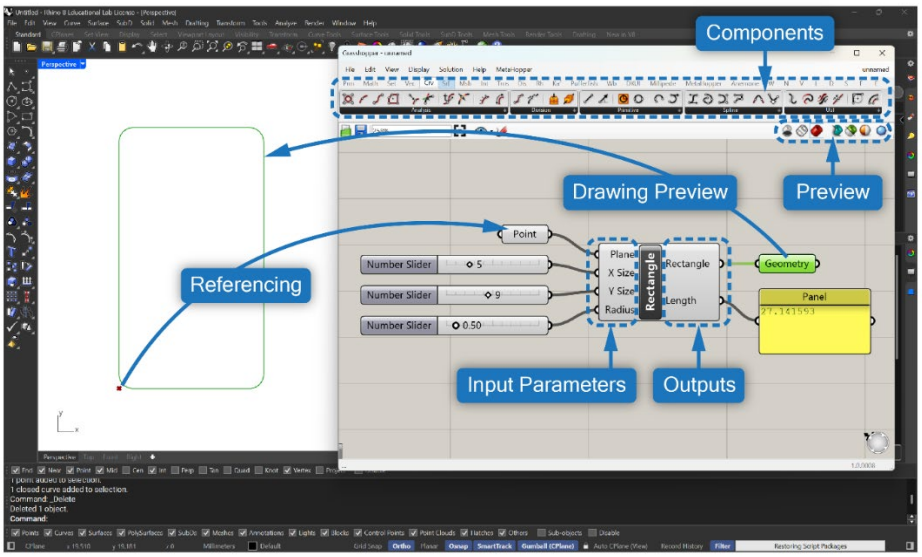

***Figure 1**: User interface of Rhinoceros 3D and Grasshopper. The interface displays the Rhino modelling environment alongside the Grasshopper visual programming canvas, where parametric definitions are created using interconnected components.*

3. Parametric Design of Architectural Typologies

This section investigates the potential applications of biofoams within architectural typologies through a series of parametric design studies. Composed of cellulose, water, and natural fibres, biofoam materials possess distinctive characteristics, including low weight, high porosity, and hygromorphic behaviour [10] . Building on these attributes, the study examines the design potentials of architectural typologies such as adaptive façade systems, self-shaping insulation and acoustic wall panels, and shading canopies. Design alternatives are generated through parametric modelling. These explorations establish a basis for translating the unique material properties of biofoams into innovative architectural applications.

3.1. Adaptive Façade Systems

A recent case study on weather-responsive shading in building façades using cellulosic composites has successfully demonstrated the applicability of bio-based cellulosic materials in an architectural context [11]. Building on the humidity responsiveness of cellulose, the biofoam material system exhibits a distinct hygromorphic behaviour. When exposed to environments with high relative humidity (RH), the extruded biofoam beads undergo radial swelling relative to the printing direction [10]. Hence, as illustrated in Figure 2, the orientation of cellulose microfibrils can be controlled through the design of printing paths to achieve anisotropic swelling, thereby enabling the bending of printed biofoam systems. Based on this principle, a parametric design workflow for adaptive façade systems is developed as shown in Figure 3. The workflow enables the systematic exploration of façade geometries and hygromorphic behaviours by parametrically linking design inputs, such as panel geometries, dimensions, and cellulose fibre orientation, to anticipated performance outcomes.

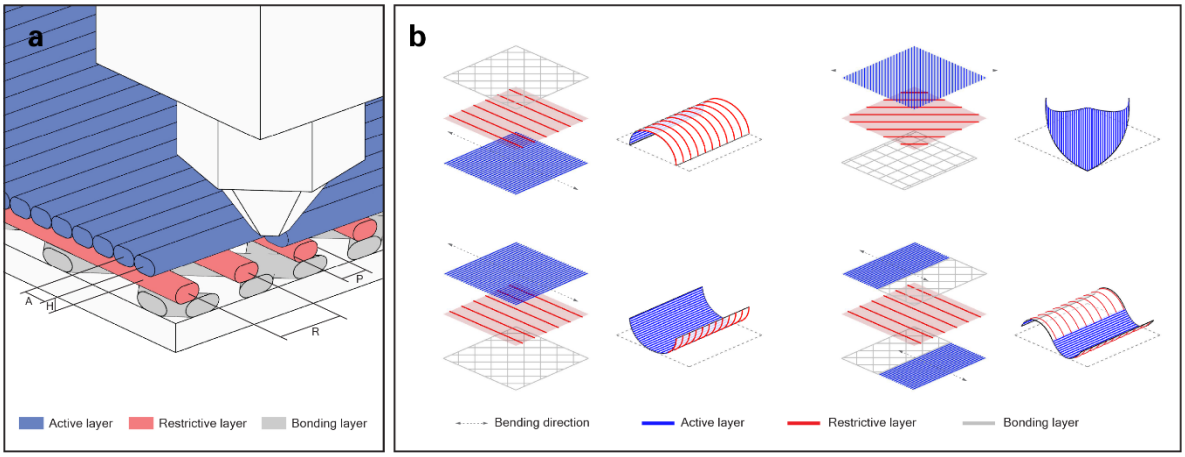

***Figure 2**: Programmed bending behaviour of printed biofoam systems from controlled print-path orientation. **a**. Additive manufacturing of mesostructures. **b**. Example of mesostructure designs yielding different shape transformations.*

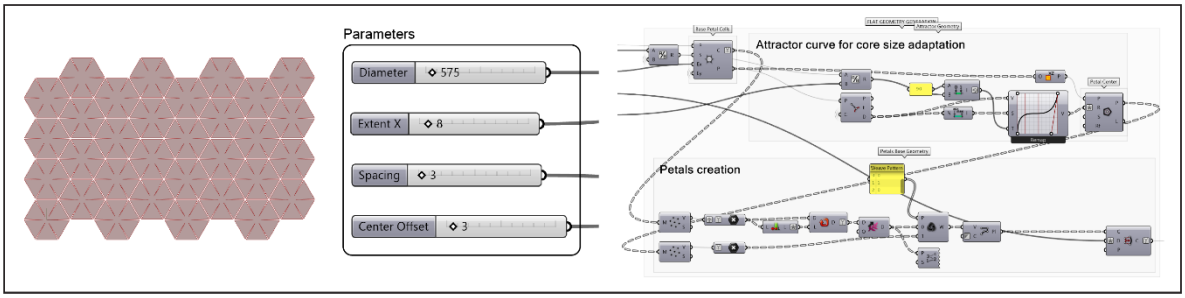

***Figure 3:** Parametric design workflow of adaptive façade systems.*

Using this framework, a series of adaptive façade system designs is generated, as illustrated in Figure 4. The explorations include a range of panel configurations, from simple diamond-shaped modules to more complex flower-petal arrangements. Each geometry is parametrically modelled to examine how different forms can open and close in response to changing conditions, demonstrating the potential of biofoam-based panels to adapt their shape and function dynamically. Beyond their functional benefits, the variations also highlight the aesthetic versatility of the approach, generating distinctive visual effects across the building surface, as shown in Figure 5. These responsive mechanisms demonstrate how adaptive façades could regulate daylight, ventilation, and shading within buildings, thereby reducing reliance on conventional mechanical systems.

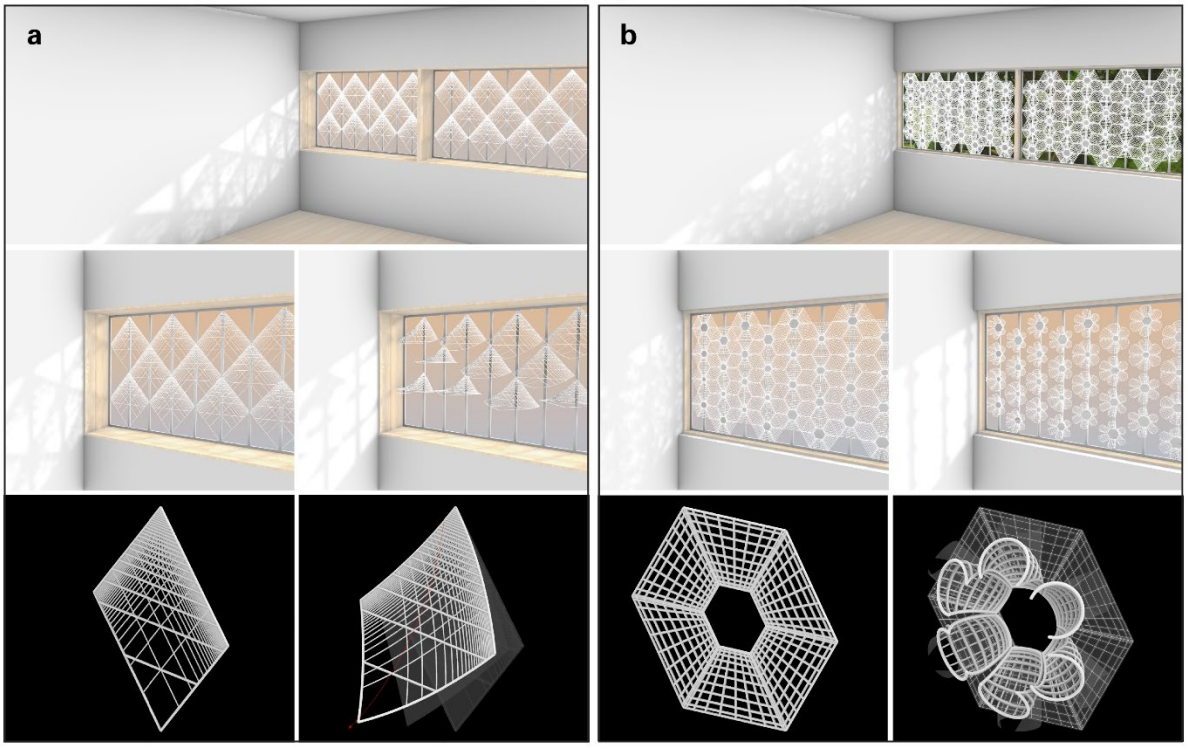

***Figure 4**: Adaptive façade system design iterations using the developed parametric design workflow. **a**. Diamond-shape module design. **b**. Flower-petal module design.*

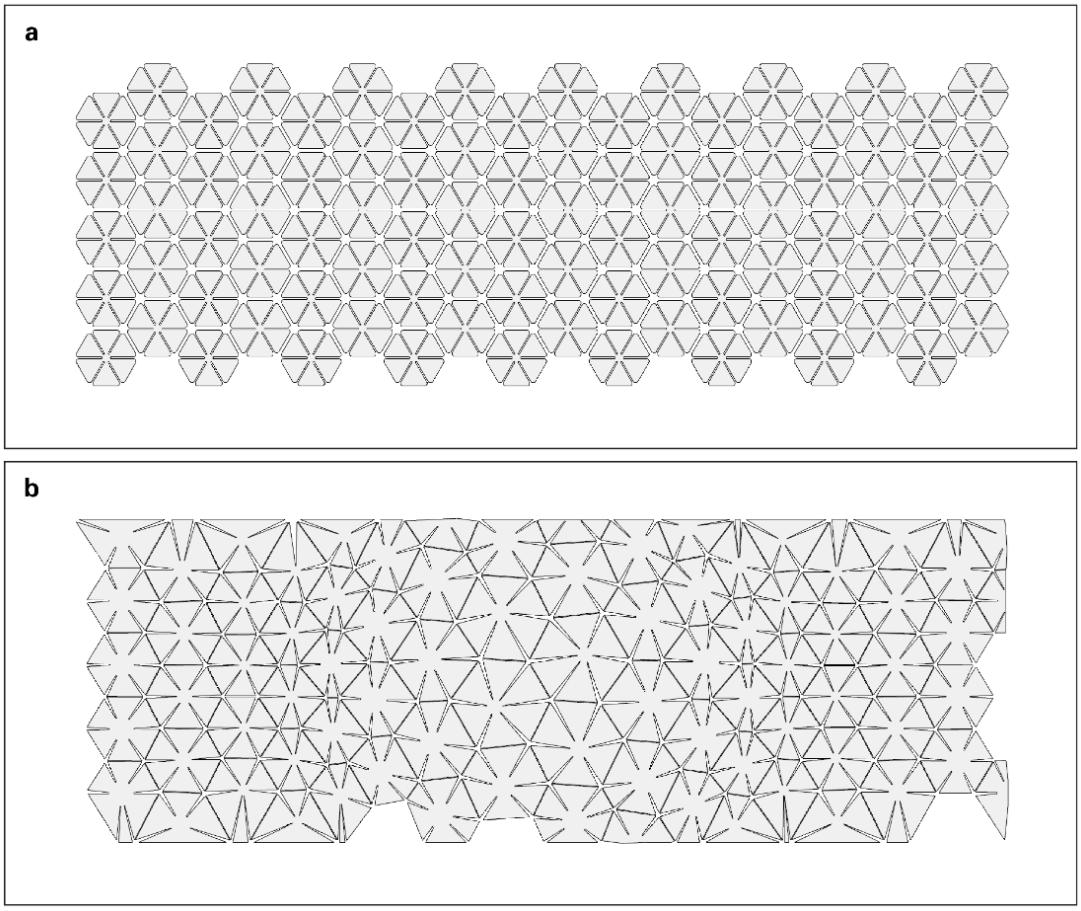

***Figure 5**: Design example of adaptive façade system with **a.** regular panel geometries, **b**. variable panel geometries, illustrating how variations in panel geometries generate distinct visual effects.*

3.2. Self-Shaping Insulation and Acoustic Wall Panels

The biofoam material system is composed of more than 50% air, providing excellent insulation performance owing to the low thermal conductivity of air [12]. The high porosity of the printed biofoam system, as illustrated in Figure 6, further enables effective acoustic energy dissipation, allowing it to function as a bulk absorber. These properties position the biofoam material system as an ideal candidate for multifunctional building components that require both thermal insulation and acoustic performance.

In addition, the biofoam system exhibits significant vertical shrinkage during the drying process, as shown in Figure 7. This unique material behaviour can be strategically harnessed by controlling printing parameters such as panel geometry and printing direction, enabling the fabrication of wall panels that undergo predictable shape change. As such, biofoam wall panels can self-shape to specific wall curvatures or design intents without the need for complex moulds or mechanical formwork. This offers

a novel method for producing self-shaping architectural panels that integrate insulation, acoustic absorption, and form-adaptability within a single material system. Such an approach not only simplifies the manufacturing process but also opens new possibilities for responsive and material-efficient construction. The ability to encode form transformation into the material's drying behaviour allows designers to generate complex geometries from initially flat prints, thereby reducing material waste and energy consumption associated with conventional forming techniques.

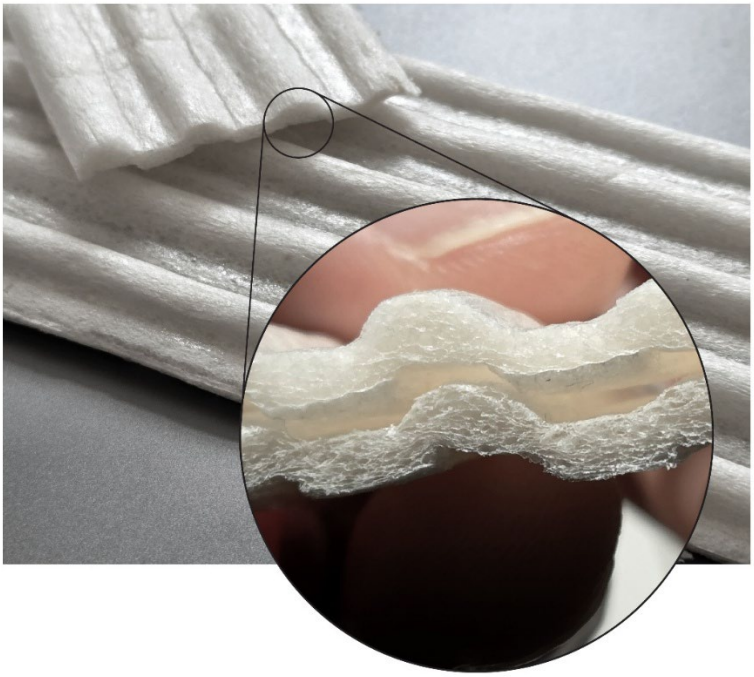

***Figure 6**: High-porosity biofoam suitable for thermal insulation and acoustic absorption.*

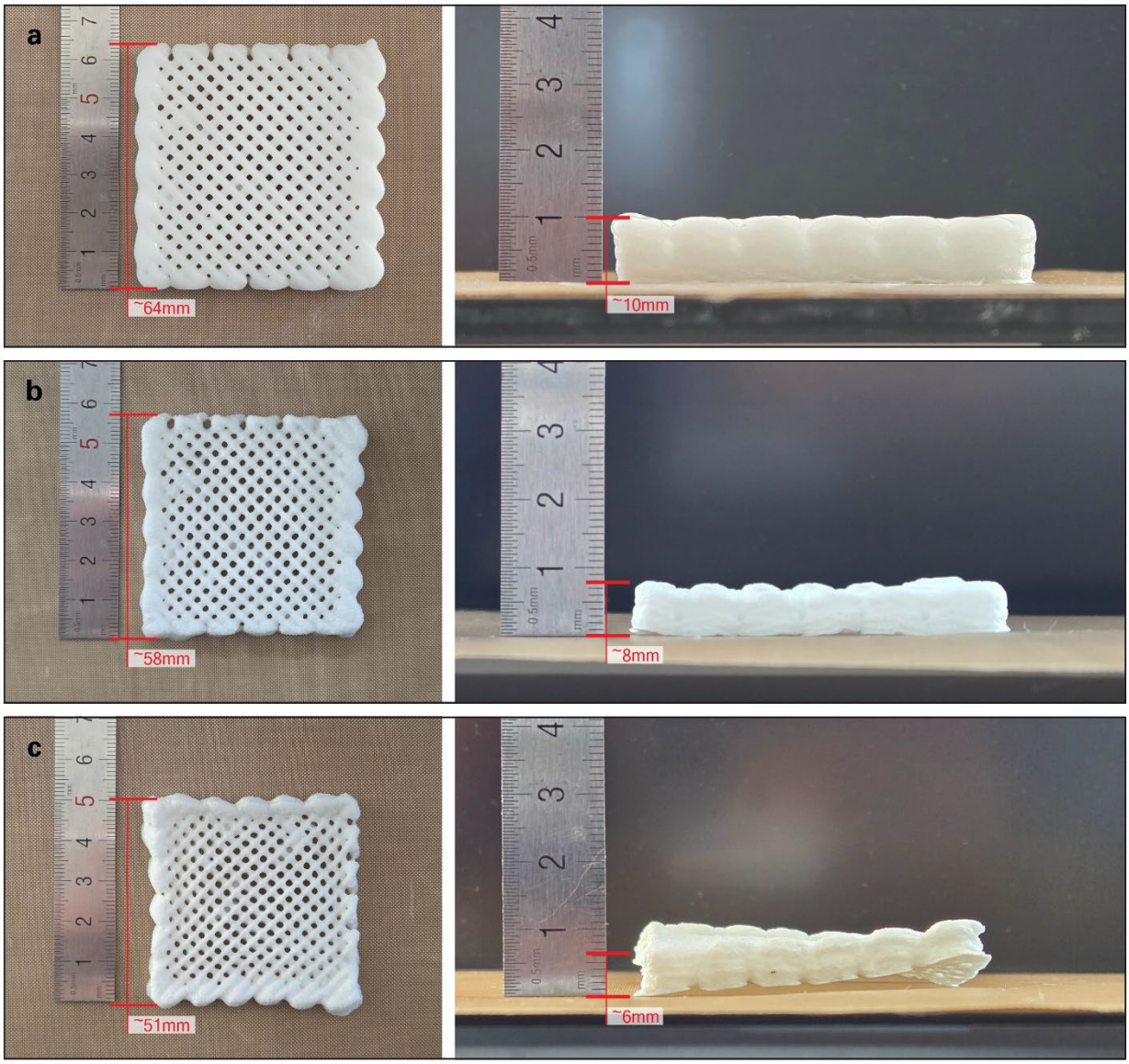

***Figure 7**: Printed biofoam sample. **a**. Immediately after deposition, prior to drying, **b**. one hour after drying on a heated bed at 75°C with an ambient space heater, **c**. fully dried showing significant vertical shrinkage.*

Building on this principle, Figure 8 presents the parametric design workflow for creating self-shaping insulation and acoustic wall panels. By utilising the distinctive shrinkage behaviour of biofoam during the drying process, wall panels can be programmed into specific geometries that accurately fit into user-defined spaces with customised curvature and customised wall profiles. The workflow integrates multiple design parameters, including panel curvatures and surface textures, allowing designers to parametrically link these inputs to predicted thermal and acoustic performance outcomes.

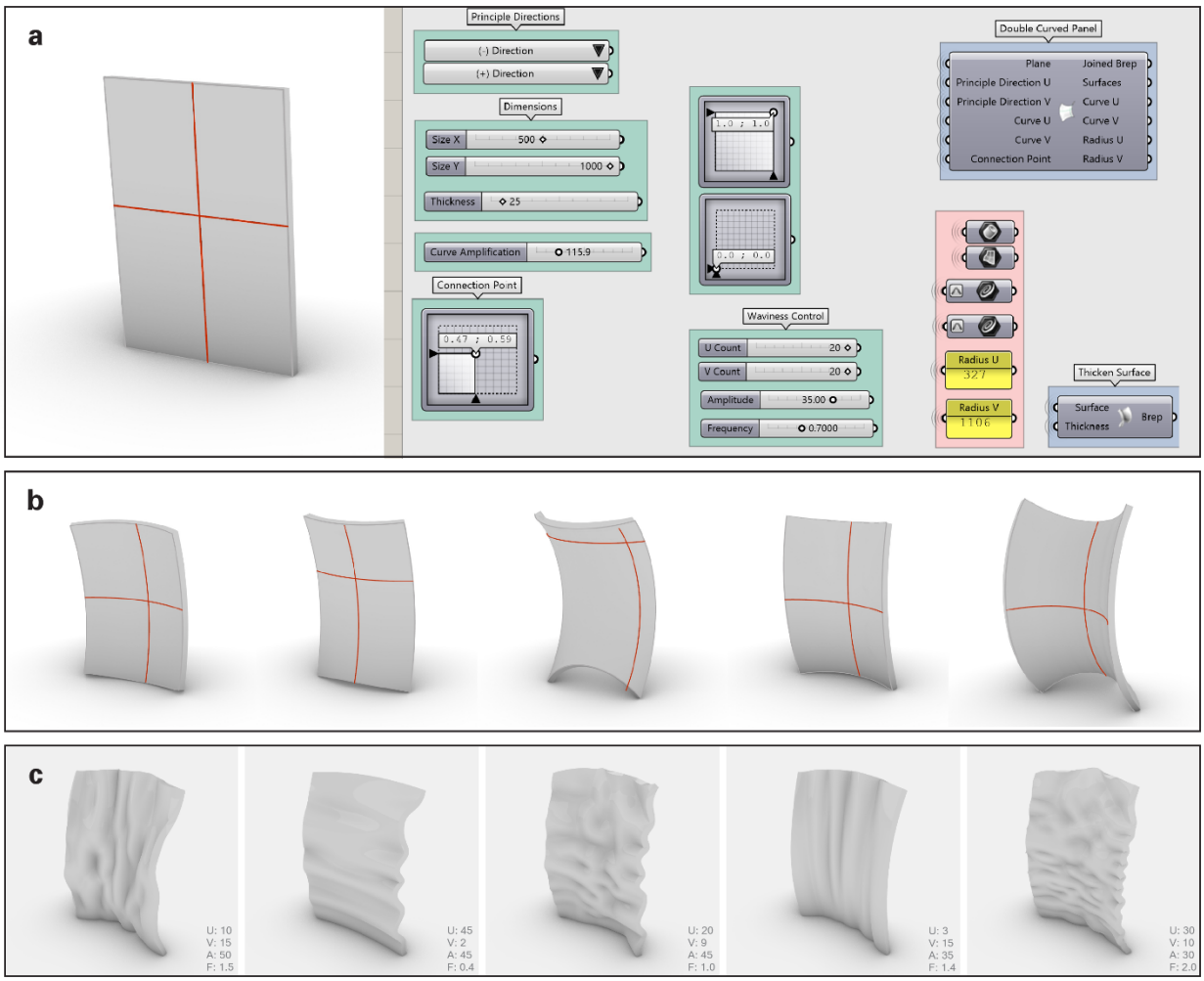

***Figure 8**: Parametric design workflow of self-shaping insulation and acoustic wall panels. **a**. Computational workflow with user-defined parameters such as principal curvature directions, frequency, amplitude, and size. **b**. Panel design iterations with tuneable Gaussian curvature. **c**. Panel design iterations featuring reflective surface textures.*

In addition to the single-panel design workflow, a complementary parametric design workflow focusing on the segmentation of wall surfaces into modular panels is developed, as shown in Figure 9. This workflow enables the discretisation of a continuous wall surface into a matrix of repeating modules using a rectangular grid pattern. Within this framework, each panel functions as an individual design domain in which unit-cell geometry, scale, and density can be precisely controlled through parametric inputs. Two illustrative examples, one employing a hexagonal unit-cell pattern and the other based on a chevron-like configuration, are presented in Figure 9. This approach allows for the strategic variation of panel characteristics across the wall surface, enabling performance-driven modulation of thermal and acoustic behaviour through geometric and topological differentiation.

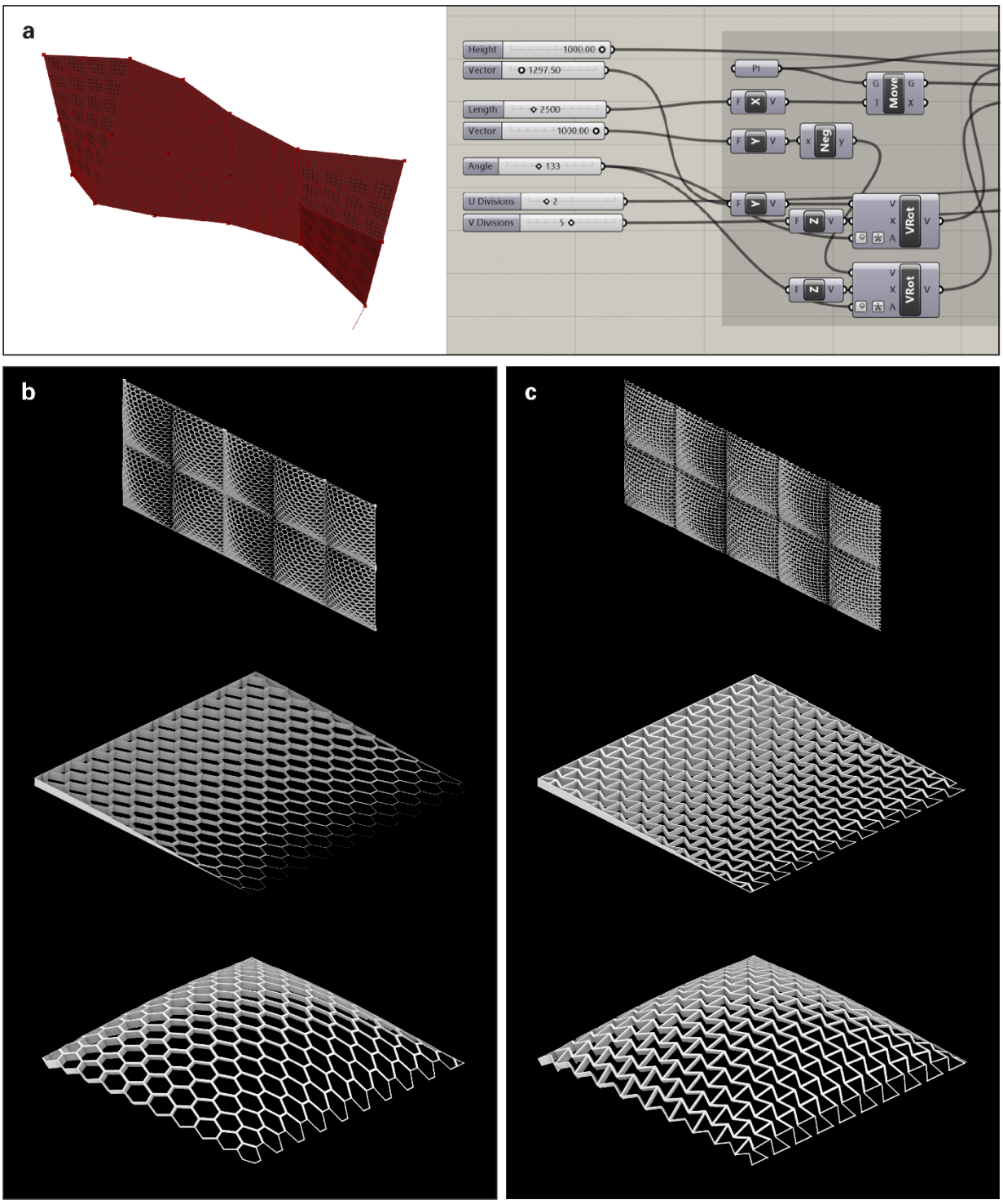

***Figure 9**: Parametric design workflow of self-shaping insulation and acoustic wall panels focusing on modular wall subdivision. **a**. Computational workflow with user-defined panel dimensions. **b**. Panel design iteration with hexagonal unit-cell pattern. **c**. Panel design iteration with chevron-like unit-cell pattern.*

3.3. Shading Canopy

The biofoam material system, characterised by its exceptionally low density of around 18.8 kg/m^3 [13], presents unique opportunities for lightweight architectural applications. Its minimal weight enables greater flexibility in form-finding and structural experimentation, opening avenues for the development of self-supporting shading canopies and pavilion systems that address both functional and aesthetic requirements. Unlike conventional construction materials, which often rely on substantial supporting frameworks, biofoam makes it possible to realise large-span canopy structures with only minimal supports. This property significantly expands the architectural possibilities for deployable and environmentally responsive systems, positioning biofoam as a material that can combine lightweight performance with adaptability and biodegradability.

Building on this potential, a parametric design workflow is developed as shown in Figure 10. The workflow controls print paths to vary the amount of deposited material across a continuous surface, thereby programming the overall canopy curvature while simultaneously regulating local transparency. Higher material deposition results in less deformation but greater opacity, while reduced deposition produces stronger deformation and more open, translucent zones. This density variation directly regulates solar exposure and indirectly contributes to the canopy's capacity for self-support, which is enabled by the intrinsic lightness of the material. As demonstrated in Figure 11, the resulting gradient surfaces create both functional and expressive effects: filtering daylight through porous lattices or forming continuous sculptural geometries with stronger shading performance. In this way, the shading canopy exemplifies how material behaviour and digital design control can be integrated into architectural applications.

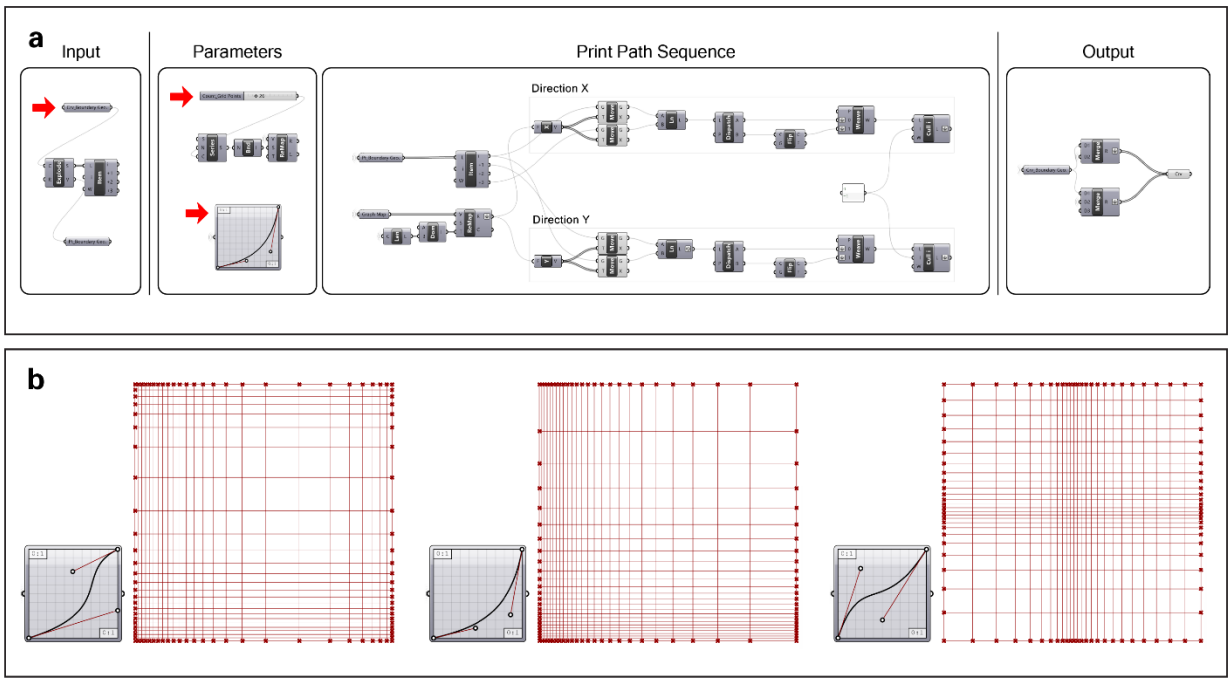

***Figure 10**: Parametric design workflow of shading canopy. **a**. Examples of print-path strategies with varying local deposition densities. **b**. The workflow links material distribution to programmed curvature and transparency, providing a basis for design exploration.*

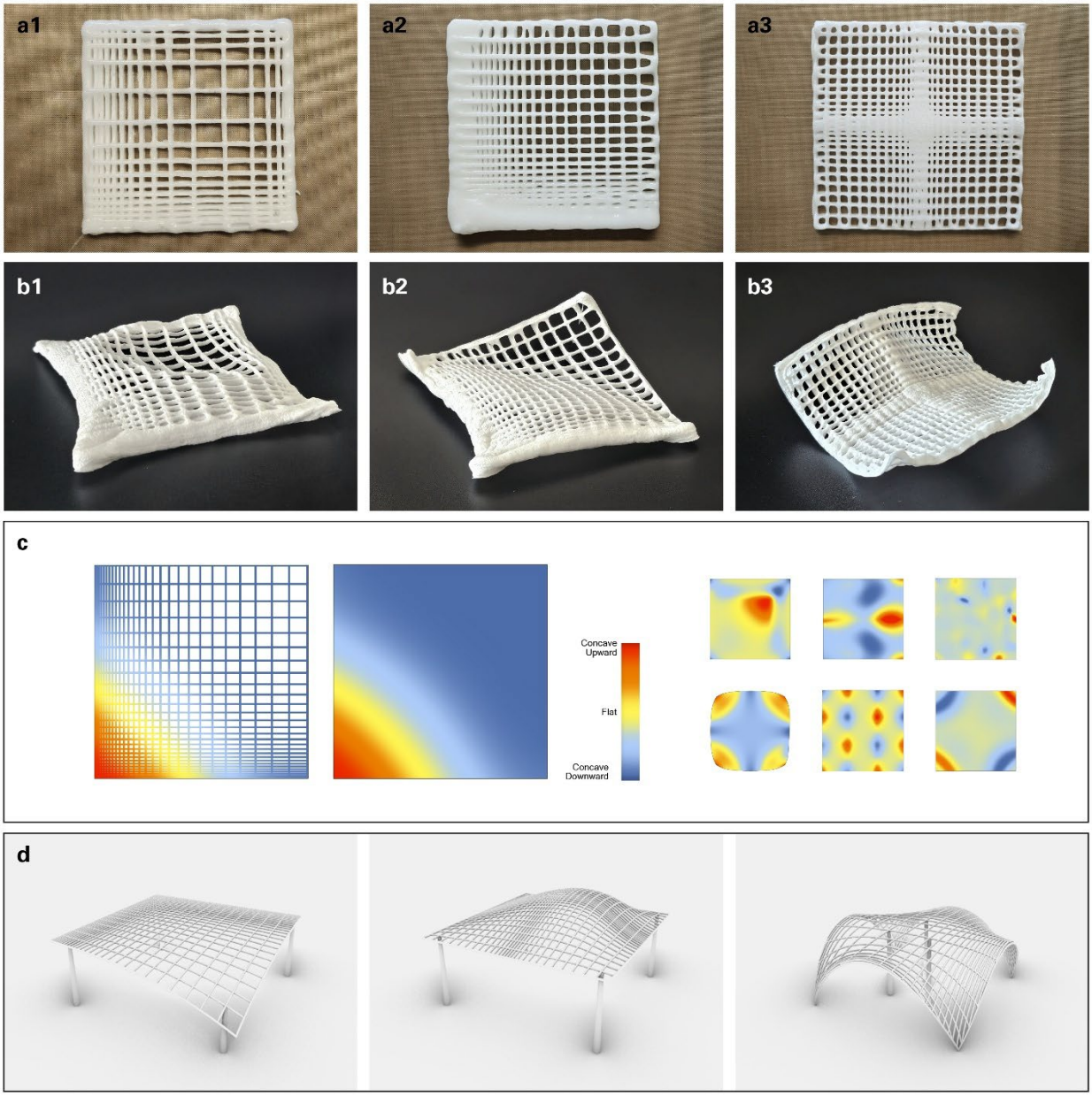

***Figure 11**: Shading canopy prototypes and design applications. **a**. Desktop-scale printed biofoam samples immediately after deposition, prior to drying. **b**. Fully dried samples exhibiting pronounced shape change due to differential shrinkage. **c**. Curvature colour map illustrating the deformation profile across the canopy surface. **d**. Conceptual rendering indicating how the system could be applied as a large-scale shading structure.*

4. Robotic Additive Fabrication

To support the robotic fabrication of the proposed architectural typologies derived from the parametric design studies, this section outlines a large-scale additive manufacturing workflow based on the robotic computational fabrication framework developed at the Institute for Computational Design and Construction (ICD), University of Stuttgart. Using this workflow, design geometries and printing process parameters are translated into toolpaths and motion primitives. A robotic simulation is also integrated within the workflow to enable the direct evaluation of robot motions. By coupling parametric design, process planning, and robot motion verification in a single environment, the framework provides an end-to-end, fabrication-aware pipeline for reliable, scalable robotic additive manufacturing.

4.1. Robotic Additive Manufacturing Workflow

Figure 12 presents the computational design-to-fabrication workflow for large-scale robotic additive manufacturing. The parametric panel design is embedded within the large-scale robotic additive manufacturing with a selected geometry provided as input. The 3D geometry is systematically processed and sliced into continuous polylines similar to desktop-scale slicing, which form the basis for robotic toolpath planning. Printing parameters, such as layer height, number of robotic planes, and printing line smoothness, are defined and adjusted. Additionally, the robot's printing strategy, orientation, location along the linear axis, speed, flow, extruder temperature, velocity, acceleration, base and tool numbers, and bed positions can be configured. Robotic simulations are then conducted based on the generated toolpaths and user-defined printing process parameters. Each printing stage can be visualised point by point to verify reachability, identify potential singularities, and ensure reliable process execution. Finally, the Source File (SRC) is generated and stored in a designated repository, ready for direct use in large-scale robotic additive manufacturing.

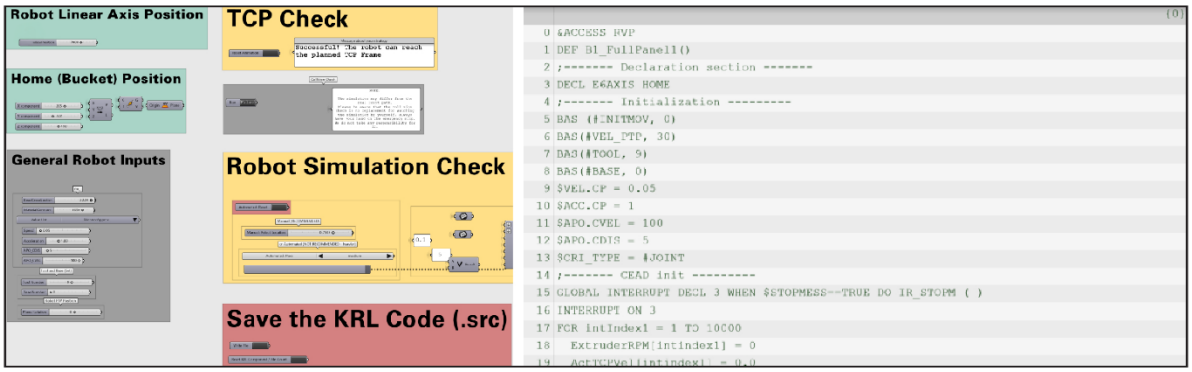

***Figure 12**: Large-scale robotic additive manufacturing workflow with user-defined printing parameters and the generated robotic file.*

4.2. Fabrication Workflow Validation

To demonstrate and validate the computational design-to-fabrication workflow, two design case studies, a wall panel with insulation and acoustic functionalities, and a shading canopy, are selected to simulation the robotic additive manufacturing process. As shown in Figures 13 and 14, the design geometries are first imported into the workflow and then sliced into continuous polylines based on the user-defined process parameters. The resulting paths are subsequently evaluated in simulation, where the corresponding robotic motions are examined for reachability and assessed for potential collisions. Through robotic-motion simulation, the entire large-scale additive manufacturing workflow is validated, confirming the feasibility of the proposed design for the selected architectural typologies.

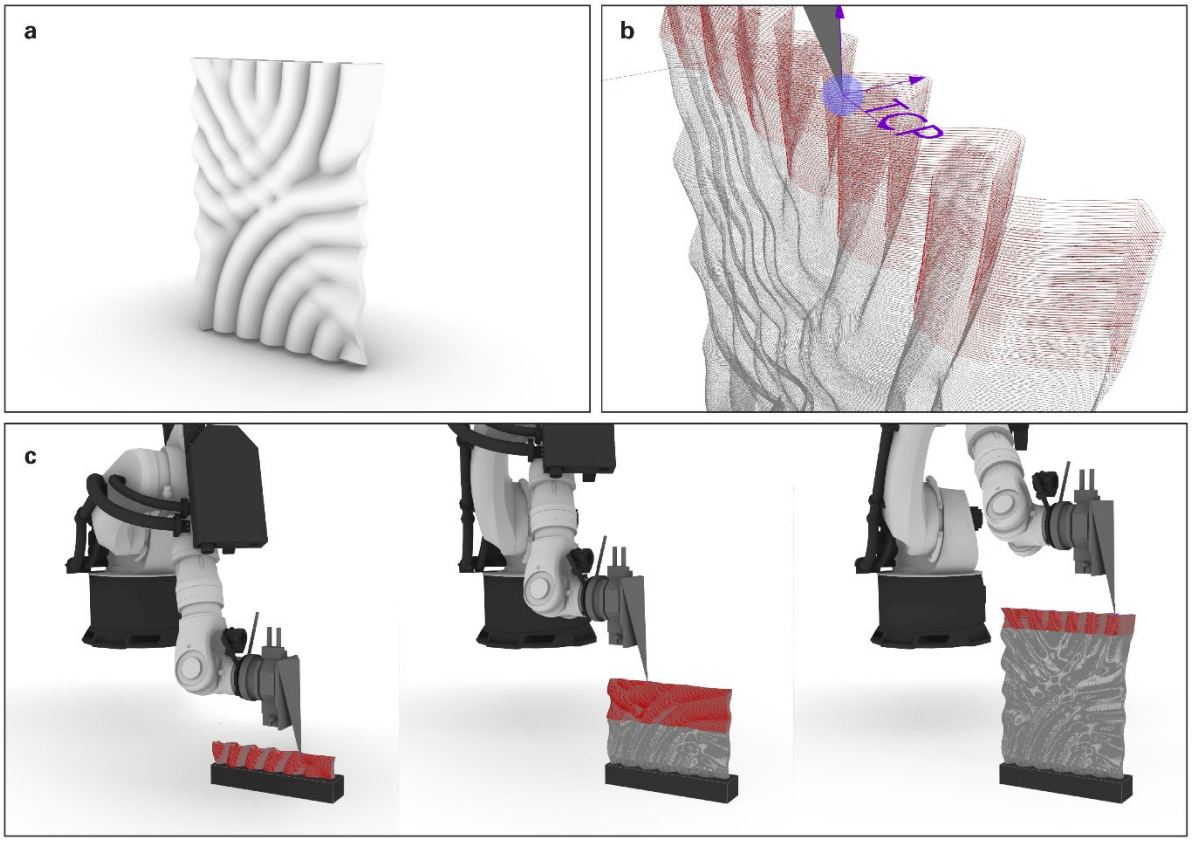

***Figure 13**: Example of a wall panel design integrated into the established computational fabrication framework. **a**. Selected design geometry is imported into the workflow. **b**. Continuous polylines are generated based on the imported design geometry. **c**. Robotic simulations are executed to evaluate the fabrication process prior to physical production.*

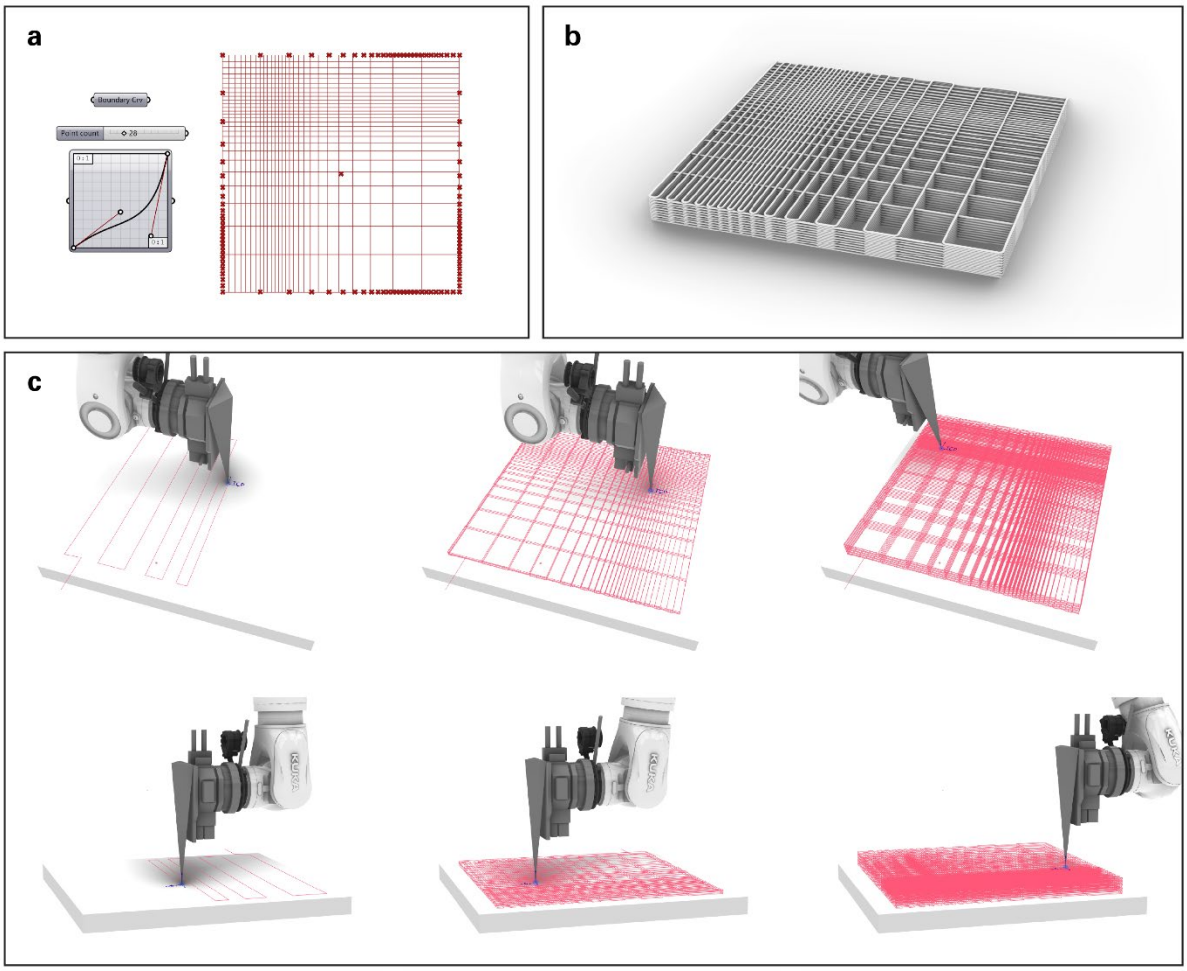

***Figure 14**: Example of a shading canopy design integrated into the established computational fabrication framework. **a**. Selected design geometry from the parametric design workflow. **b**. 3D design geometry is imported into the fabrication workflow. **c**. Robotic simulations are executed to evaluate the fabrication process prior to physical production.*

5. Discussion and Conclusion

This report presents a computational design-to-fabrication workflow for multifunctional biofoam components in architectural applications. It focuses on the parametric design, modelling, and robotic additive fabrication of selected architectural typologies. The biofoam material system, developed by the project partner Aalto University, exhibits a lightweight, porous character, and distinctive shrinkage during drying. Drawing on these unique properties of biofoams, parametric design models for selected architectural typologies, including adaptive façade systems, self-shaping insulation and acoustic wall panels, and shading canopies, are developed within the industry standard design environment using a visual programming application. A large-scale robotic additive fabrication framework is also presented in this report for translating the parametric design models into toolpaths and machine-readable code. The robotic fabrication workflow is validated through two case studies, a wall panel and a shading canopy, including an end-to-end digital simulation of the additive manufacturing process. The results demonstrate the feasibility of coupling material behaviour with performance-driven geometry to achieve a continuous, fabrication-aware design intent while reducing process complexity. The outcomes of this report provide a foundational contribution to the ARCHIBIOFOAM project by integrating adaptive design with digital fabrication workflows. The architectural typologies identified in this report will serve as case studies for the subsequent evaluation of the design software to be developed by the project partner UMIL in forthcoming tasks.

References

[1] Intergovernmental Panel On Climate Change (Ipcc). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 1st ed. Cambridge University Press; 2023. https://doi.org/10.1017/9781009157896.

[2] United Nations Environment Programme GA for B and C. Not just another brick in the wall: The solutions exist - Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025 2025.

[3] 2019 global status report for buildings and construction. Paris: International Energy Agency : Global Alliance for Buildings and Construction; 2019.

[4] Huovila H Pekka, Ala-Juusela M, Melchert L, Pouffary S, Cheng C-C, Ürge-Vorsatz D, et al. Buildings and Climate Change: Summary for Decision-Makers. Nairobi, Kenya: United Nations Environment Programme; 2009.

[5] Menges A, Ahlquist S. Computational design thinking: computation design thinking. John Wiley & Sons; 2011.

[6] Piker D. Kangaroo: form finding with computational physics. Archit Des 2013;83:136–7.

[7] Zhou Q, Shen W, Wang J, Zhou YY, Xie YM. Ameba: A new topology optimization tool for architectural design. vol. 2018, International Association for Shell and Spatial Structures (IASS); 2018, p. 1–8.

[8] Sadeghipour Roudsari M, Pak M, Viola A. Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. vol. 13, IBPSA; 2013, p. 3128–35.

[9] Braumann J, Brell-Cokcan S. Adaptive Robot Control. Bob Martens Gabriel Wurzer Thomas Grasl Wolfgang E Lorenz 2015:243.

[10] Reichler M, Rabensteiner S, Törnblom L, Coffeng S, Viitanen L, Jannuzzi L, et al. Scalable method for bio-based solid foams that mimic wood. Sci Rep 2021;11:24306.

[11] Cheng T, Tahouni Y, Sahin ES, Ulrich K, Lajewski S, Bonten C, et al. Weather-responsive adaptive shading through biobased and bioinspired hygromorphic 4D-printing. Nat Commun 2024;15:10366.

[12] Stephan K, Laesecke A. The thermal conductivity of fluid air. J Phys Chem Ref Data 1985;14:227–34.

[13] Miranda-Valdez IY, Coffeng S, Zhou Y, Viitanen L, Hu X, Jannuzzi L, et al. Foam-formed biocomposites based on cellulose products and lignin. Cellulose 2023;30:2253–66.