ANOTHER LOGIC FOR ARCHITECTURAL (BIO-) DESIGN AND FABRICATION - LESSONS FROM THE LIVING PROTOTYPES PROJECT

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Abstract

This paper argues for the transformative potential of biomaterials in architecture and highlights the need to recognize their impact on professional practice. Insights are drawn from an 18-month European research project involving three teams of academic and industry partners. The project aimed to scale up cutting-edge technologies in 3D-printed earth, flax-fiber winding, and biopolymer printing, exploring the potential and challenges of natural and biobased recycled materials combined with digital fabrication techniques. The project culminated in a 1:1 scale prototype of a living space, digitally fabricated and exhibited at the Aedes Architecture Forum in Berlin. The evaluation of the process and result shows how the strong material behaviour, temporality and heterogeneity of biomaterials required the teams to radically rethink processes of fabrication, assembly, tolerances, and joints between material systems as well, as the materials malleability provided opportunities for adaptation and caretaking. The project demonstrates the importance of digital techniques in the design and fabrication of biobased materials, including additive manufacturing, sensing, data collection, and machine learning. The paper identifies detailed lessons and practice-based methods for the shift towards natural, biodegradable, and recyclable materials- These call to rethink standardisation in the building industry, as digital technologies provide means to adapt design and fabrication to the heterogeneities of biomaterials and challenge the current practice of optimisation for minimal material usage in design as resource-efficient use of biomaterials needs to include more complex considerations of local ecology, the speed of natural growth and processing, dynamic environmental conditions, agricultural policies and cultures.

1. INTRODUCTION

Industrial techniques and technologies developed by the building and construction sector are today employed all over the world. Using the same set of materials from the geosphere, they contribute massively to the overconsumption of the earth's resources and harm the climate. By maximising the industrial strategies of scale and standardisation we sideline local material sources and available human skills and have set the building environment onto a linear path from exploitative extraction to an end-of-use scenario where materials are considered waste. A change from this practice of extracting materials from the geosphere to a sustainable and circular practice of using recycled and regenerative local materials from the biosphere is underway in research, general practice and governance [1]–[3] [4]. The shift in the material-base of the building industry towards these inherently heterogeneous material classes has disruptive potential. Biomaterials, in this text understood as materials that are gown as well as little processed mineral materials, especially earth, are characterised by their fluxile compositions and strong material behaviours over their lifespan as well as during initial processing and fabrication, because they react to changes in the environment – such as humidity and temperature, and are prone to decay – due to infestation and erosion, for example. How can the design and building of architecture move from a practice based on standardised, homogeneous and high-strength materials, to one based on potentially weaker, and ideally unprocessed biomaterials?

1.1. RETHINKING STANDARDISATION IN THE BUILDING INDUSTRY

In the past, the building industry has developed methods to address heterogeneities in biomaterials, earthen, and reclaimed materials. However, these approaches are either resource-intensive or require significant labor and knowledge to adapt to material source changes and site environments. Adaptive digital design and fabrication enable customized approaches based on the sources and life cycles of biomaterials, allowing for architecture to be defined on a project-by-project basis. This approach has the potential to minimize environmental impacts and introduce flexibility at material, conceptual, and social levels.

Digital fabrication enables affordable customization, allowing for individually designed and manufactured building elements that can be hyper-specified based on local material sources and performance requirements. Biomaterial porosities can be tailored for humidity control, and 3D-printed voids can incorporate structural joints, ventilation ducts, and technical appliances. Additive manufacturing adjusts the strength and appearance of a single material within a building element. This departure from homogeneous materials allows for material-grading in response to specific performance needs. Additionally, machine learning tools provide an alternative approach to material control, using novel statistical methods and real-world data to predict biomaterial behavior with precision, replacing traditional techniques of homogenization and classification.

These aspects redefine architecture, moving it away from standardization and fostering creativity and innovation in the building industry. The unique properties of biomaterials and the emerging local, circular, and sustainable practice challenge the relevance of ISO standards, material classes, and grades. Rethinking these standards and their rigid definitions is necessary to enable design based on behavioral control of materials. Shifting from long-term analytic-explanatory models to faster, circular predictive-accuracy models will support architecture with inherent flexibility for future adaptations.

An iterative approach with experimental tests and prototypes supports the non-standard design method described above. Adopting an experimental, prototype-based approach in architectural design involves working with predictability and margins of error instead of relying on established standards. To ensure control and safety, this may require a building practice that shifts from the notion of a finished building to continuous monitoring throughout its lifespan, utilizing data collection and interpretation. This practice embraces observation, stochastic methods, and continuous reconstruction, challenging conventional architectural design thinking and prevailing engineering concepts that lack post-construction data collection beyond energy consumption. It raises questions about which aspects require close control, the benefits and drawbacks of digital tooling options, and their associated implications.

For an innovation to become mainstream, it must undergo extensive testing and prove its worth. Introducing biomaterials into mainstream building practice requires initial experimentation, which is often not embraced by construction companies, housing providers, and property developers who prioritize risk aversion. As a result, the burden of innovation falls on smaller industry players, including architects. A more agile, open-source, risk-sharing process is required if architecture, building practice and the building industry is to redress the impact of construction on the planet in the limited time available. How can this be achieved in a generally risk-averse industry and society?

1.2. BIOBASED AND EARTHEN MATERIALS - GOING BEYOND THE PRIMACY OF OPTIMISATION

The work underlying this paper is rooted in the field of digital design and fabrication in architecture and engineering. To date, the main emphasis in the field has been on the efficient use of construction materials. Under the banner of "less is more" (Ludwig Mies van der Rohe) or "how much does your building weigh" (Buckminster Fuller), generations of architects and engineers have searched for the optimal use of materials and structures; most often meaning high strength, low cost and minimal use of (high-tech) materials. With grown, earthen and reused materials this logic disperses. These classes of material move the emphasis away from minimisation towards other kinds of architectural ideals and logics.

Their lower levels of standardisation and durability – in comparison to those of established fossil materials – result in an increase in material-usage in design, thereby shifting the concept of material optimisation from simply minimising structural weight to an alternative consideration of structural redundancy. This not only answers the need for mass for sound insulation and energy-buffering in light-weight structures, but also contributes to the quest for carbon net-positive buildings by carbon storage in biogenic mass [5].

However, a simple increase in the amount of material used is neither an answer with regard to cost nor the implications on architectural or environmental level, where the photosynthetic ceiling sets a limit on how much biomass humans can use in a sustainable way.

This calls for a new way to understand resource-efficiency that enables designers to navigate the new complexities of biomaterials. These complexities do not solely arise from the variation in material performance, but also from considerations of local ecology, the speed of natural growth and processing, dynamic environmental conditions through seasons and events –such as storms, pest and drought –that impact availability and quality, agricultural policies and cultures. The required redundancy hence also resides in the expanded range of possible options with biomaterials, providing flexibility towards material selection depending on the site and resource availability. Additionally, there are also local variables that often only emerge through deep engagement with local processes and human actors. What are design systems and frameworks for optimisation that are open to the incorporation of such emerging factors?

2. THE LIVING PROTOTYPES PROJECT – PROTOTYPING A NEW PRACTICE IN ARCHITECTURE

The Living Prototypes research project was a collaboration between ANCB The Aedes Metropolitan Laboratory and three European research teams. Its objective was to create resource-efficient prototypes for living spaces using digital fabrication and biobased materials. These prototypes aimed to generate public interest, build confidence in the construction industry, and showcase the feasibility of the proposed designs. The main objective of the Living Prototypes project was to demonstrate and communicate the added value of biomaterials and digital fabrication for architectural practice in terms of design potential and resource-efficient building, by making this tangible and experienceable. The development of the digitally manufactured prototypes took place over a period of one and a half years and culminated in a 1:1 demonstrator (Figure 1).

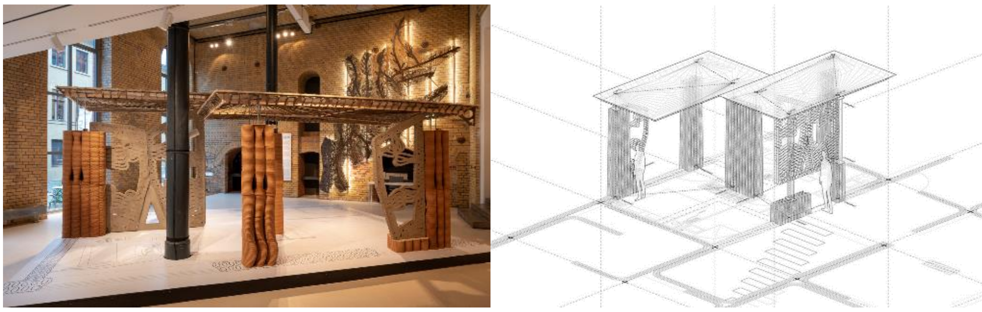

Figure 1. The Living Prototypes exhibition at the Aedes Gallery © Erik-Jan Ouwerkerk (left) Design sketch of the integrated 1:1 prototype - new idea - making a space, bringing prototypes together (right)

The three research teams worked with the biobased material systems of earth, flax and bioplastics, which are complementary in their sources, properties and potential areas of application in the building sector. The research teams and their projects were:

3D-Printed Earth - University Partner: IAAC – Institute for Advanced Architecture of Catalonia, Barcelona. Industry Partner: WASP, Massa Lombarda

Flax Fibre Winding - University Partner: ITKE – Institute of Building Structures and Structural Design, University of Stuttgart. Industry Partner: FibR GmbH, Kernen

Bioplastic Prints - University Partner: CITA – Centre for Information Technology and Architecture, Royal Danish Academy, Copenhagen (Research Coordinator).Industry Partner: COBOD International A/S, Copenhagen

For ANCB The Aedes Metropolitan Laboratory – the project curator and coordinator – the Living Prototypes project was an opportunity to apply expertise in architectural communication in the context of a scientific research project, both in terms of methodological process and outcomes; by providing a physical and intellectual space experimental collaboration between the three research teams, including ongoing discussion of the interim and final results with the public and the architecture community.

The research project was designed to conclude in an exhibition at Aedes Architecture Forum in Berlin over 6-weeks from 10.12.2022 - 25.01.2023, in which 1:1 prototypes of living spaces fabricated from biomaterials could be experienced and discussed. As a low-threshold translation of abstract laboratory research, the exhibition of the prototypes aimed to illustrate for the public, the construction industry and politics the architecture possible with biobased materials and digital manufacturing techniques.

The project was accompanied by several public events that brought a highly current topic closer to a wider public in a tangible way by means of two workshops that took place in parallel to the development of the prototypes, and a symposium just before the exhibition opening.

3. METHOD

The project employed an iterative and design-based research-by-design method, using physical experiments to evaluate architectural parameters. Collaboration with industry partners and regular communication facilitated the development process. An advisory board was established to provide practical guidance and feedback. Experts from architectural practice, research, building industry, and political initiatives were involved to advise on materiality, prototype development, innovation, CO2 reduction, and resource efficiency. Representatives from housing associations were also engaged, despite their limited interest in the project.

3.1. PHASE 1: SCALING UP

The iterative process underpinning this methodology is structured with phases of speculation and ideation, small-scale tests and full-scale prototypes. The Living Prototypes project went through two of these cycles, each of informed by an onsite workshop involving all members of the research partnerships. The first phase of prototype development was concerned with scaling up of the material- and related design and fabrication systems within each of the three industry-academia teams (Sept. 2021 to Feb. 2022). In this phase, the teams developed the design and technical solutions for the fabrication of their prototypes, including the assembly and joining of parts within their respective systems. Additionally, this phase found its physical manifestation in a series of individual large-scale prototypes [7], [8]) fabricated by individual teams.

3.2. PHASE 2: INTEGRATED 1:1 PROTOTYPE

The process took a decisive turn during the interim workshop, when an opportunity to go beyond the project brief was identified by integrating the three material systems into a single prototype thereafter shifting the focus of further research to the integration and interfacing of the three material systems.

The installation was conceived with the aim of suggesting a very familiar space – our homes – as concretely as possible in order to stimulate the imagination of the visitors: they were encouraged to perceive the exhibition with all their senses, to touch and smell the prototypes. It was decided to bring the three material systems together in a 1:1 living space installation, integrated into the floor plan of a typical two-room apartment. Guiding questions were identified to guide the exhibition visitor, namely: What might our homes look and feel like if they were built without the use of fossil fuels? What if research into biobased building materials could bring about a profound change in the way architecture is designed and built?

Figure 2. Speculative visualisation of the use of 3D printed earth for urban multi story buildings @3DPA (left); Board with 3D printed biopolymers in the Living Prototypes exhibition © Erik-Jan Ouwerkerk.

It was decided to prepare speculative visualisations of the architecture possible with these biomaterials and digital fabrication methods. The development of the biomaterials and prototypes during the project were to be illustrated with video and photographic material, as well through the inclusion of raw material samples and probes from further research by each team (Figure 2).

Once this common vision was established within the partnership a joint iterative process was established, encompassing the proposition and discussion of designs, testing of the consequences of these for the three material systems through simulations and small-scale tests, and the discussion of technical details across shared digital models and communication platforms.

The design of the prototypes was finalised in August 2022. Thereafter, the individual elements were produced on large-scale machines. However, even in this production phase, prototypes were iteratively adapted due to input from partners both in materiality and in geometrical definition. Video conferences were held weekly from mid-August until late-November to coordinate the design of the prototypes and the complex logistics of exhibition planning in detail.

4. THREE BIOBASED MATERIAL-SYSTEMS

Through its setup, the project provided means to gain insights into the logics, processes, and challenges within three biobased material systems, especially in regard to the effects that their scaling--up to that architectural scale have. This chapter outlines these effects for each individual material system, while the next one investigates the interrelation and dependencies between them in the 1:1 prototype.

4.1. BIOPLASTIC PRINTS

Bioplastics possess renewable, low-cost, biodegradable, and versatile properties. Utilizing additive manufacturing and data analysis, like machine learning, enables prediction and control of these materials' behavior during and post-printing. The biopolymer employed in this project is mixed during printing, facilitating real-time variation of the recipe to adapt material properties locally (Grading) (Figure 3). The CITA-COBOD prototypes for interior components employed two complementary biobased materials: cellulose and collagen.

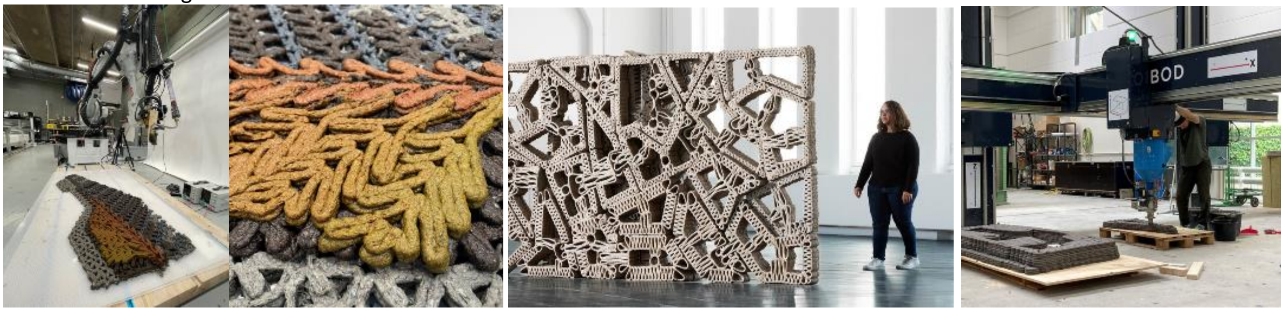

Figure 3. The grading of the cellulose source (e.g. recycled paper, bark, linen, cotton) as well as to the binder (Xanthan or bone glue) can create a variety of material expressions and behaviours. International Academic Workshop of CITA at 2022 ACADIA conference - Penn University (left). Cellulose Wall demonstrator exhibited in Copenhagen (2021) @Anders Ingvartsen, Printing of Cellulose Screens on the COBOD BOD2 542 gantry 3D-printing system - June 2022 @CITA (right)

Cellulose Screens

The CITA-COBOD subproject Cellulose Enclosures scaled up a cellulose-based biopolymer from recycled paper [9] for architectural-scale components. Small-scale robotic printing at CITA was extended to large-scale gantry-based production using a COBOD printer, resulting in a full-scale prototype in December 2021 (Figure 3). The existing print setup was modified with a new pumping system, allowing the production of approximately 70x70x15 cm pieces. Shrinkage behavior was monitored [10], and machine learning successfully predicted the biopolymer's behavior using physical probe data [11].

Curing time was a bottleneck for the cellulose/xanthan material. Redesigning the printed element with internal air channels and an undulating print path maximized surface area, improved convection, and achieved a unique visual expression [7]. In the second phase, the cellulose/xanthan-based biopolymer was successfully printed on the COBOD BOD2 542 gantry system, currently the largest on the market, without recipe modifications. Large screens (max 90 x 250 cm) were printed in June 2022 for the Living Prototype 1:1 demonstrator (Figure 3), with initial drying conducted using minimal energy in a controlled environment with dehumidifiers for one month.

Collagen 3D printed Wall Panels - Radicant

The biopolymer recipe was tested on the 'Radicant' demonstrator, a 7x5 m prototype exhibited at the Living Prototypes exhibition. Collagen replaced xanthan as the binder, resulting in shorter curing times and the ability to create graded materials. This required significant changes to the print setup, including the development of a heated robotic 3D printing system. The novel collagen printing process was used in Radicant's bespoke wall-panelling system, where the biopolymer composite was reinforced with cellulose from waste products. Different compositions of biopolymer composites were 3D-printed as tiles, forming a branching, interwoven form that gradually varied from bottom to top. The adaptation of the biopolymer system and the development of protocols, printing tools, and design processes took less than five months [12]. Although collagen curing took about two weeks, uneven shrinkage occurred in the elements. A feedback loop was established by 3D scanning the cured panels to capture changes during drying, updating the digital design model for accurate fabrication. Minor deviations were addressed through a tolerant mounting system and guided assembly using a LAP laser projection system (Figure 4).

Figure 4. Bespoke wall-panelling system “Radicant” installed in the Aedes Architecture Forum 2022 @Anders Invartsen (left). Overlay of the grading of the leaf layer on the base layer of tiles (middle), Assembly augmentation using laser projection (right).

4.2. EARTH 3D PRINTING

Earth is a traditional, cost-effective, and locally available building material that has been used for centuries in architectural constructions [14]. It is an integral part of adobe, one of the earliest composites [15]. Earthen architecture offers numerous advantages over common building materials, including thermal mass, durability, low environmental impact, recyclability, and cost-effectiveness.

Additive manufacturing has revolutionized earth architecture by challenging traditional construction methods and introducing new possibilities [16]. This technology combines material science, machine systems, and traditional techniques to explore novel mechanical and aesthetic properties. However, the use of slurry-based earth materials in additive manufacturing presents challenges in design and fabrication. The material's wet and dry states with distinct mechanical, dimensional, and weight properties complicate the design-to-production process. Additionally, the Living Prototypes project encountered challenges in defining the geometry of large unbaked pieces based on prefabrication principles.

Resolution of material optimization

The IAAC's Living Prototypes demonstrator featured load-bearing walls with jointing details for interfacing with other biomaterials [19]. Due to on-site printing limitations, separate pieces were designed, printed, dried, transported, and assembled in Berlin.

A new infill pattern design based on closed loops was created for the walls to address material shrinkage and deformation issues [20]. Closed-cells and continuous loop-shaped cavities within the printed pieces allowed for controlled shrinkage and ensured dimensional accuracy within design tolerance.

The use of a premixed material posed limitations due to changes in rheology caused by ambient humidity, resulting in uneven results in the 3D printed beads. However, the bio-based material (earth soil, clay, sisal fibers, and water) used in the project is 100% recyclable, allowing for rehydration and recycling if wet-state collapse or moisture-related issues occur (Figure 5) [19]. [17].

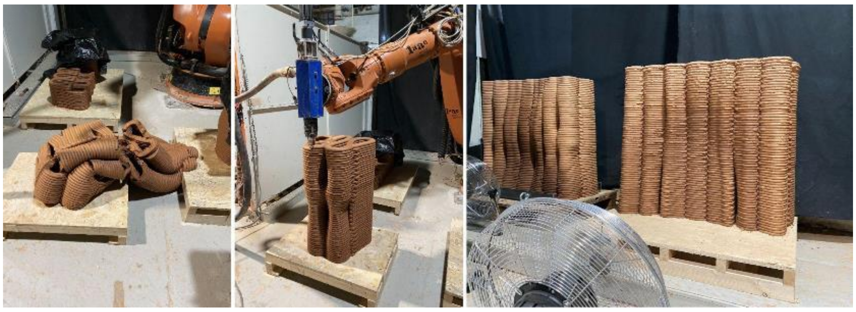

Figure 5. Collapsed piece (left). Printing with recycled material (center). Drying with ventilation (right) © IAAC 3DPA 2022-2023

The design of the earth components involved validation, quality control, and attention to printing speeds, deposition rate, and ease of transportation for assembly. The final exhibition prototype showcased the system's adaptability in terms of performance (structural, acoustic, and thermal), interface capability, and material aesthetics [19].

Standardization and off-site prefabrication of bio-material systems

Logistical challenges during the construction of the TOVA prototype (Figure 6) at IAAC Valldaura campus led to the decision to produce the exhibition prototype off-site. The earth-printed pieces were limited in size and weight to fit standard pallet dimensions, and specific premixed materials were used instead of on-site excavation materials.

Figure 6. TOVA Prototype (left). Opening detail (center). Ventilation shaft (right), IAAC 3DPA 2021-2022. ©Gregori Civera

The TOVA prototype aligns with IAAC and WASP's goal of shipping the large-scale printer to the construction site and utilizing local material. On-site printing processes result in non-homogeneous drying, which can lead to cracks and fabrication defects due to rapid moisture changes. Monitoring and addressing defects promptly is essential to prevent structural issues.

For transportation to Berlin, the components were printed in two parts and deposited on custom-made bases to ensure safe transportation and enable strapping for heavy and delicate elements. The design included connection details for element stacking. In Berlin, the earth pieces were hoisted and stacked together (Figure 7). To prevent cracking during transit, the elements were shipped before fully drying, taking advantage of the material's plasticity. The final drying would occur with the pieces stacked and loaded by other biomaterial elements.

Figure 7. Pieces drying during shipping (left). Transport of 3.2Tn (center). Stacking of pieces (right) © IAAC 3DPA 2022-2023

4.3. FLAX FIBRE- WINDING

The ITKE – FibR research focused on exploring lightweight natural-fibre structures using coreless filament winding. Robotically fabricated composite structures reinforced with natural fibres offer a sustainable alternative to conventional construction methods, with excellent strength-to-weight ratio. Co-design processes considering various requirements and advanced robotic fabrication techniques applied to natural materials result in unique, performative structures (Figure 8) [17].

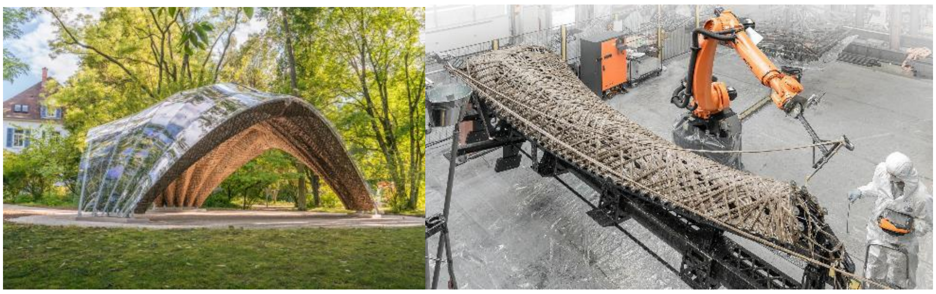

Figure 8. LivMatS Pavilion 2020-21 external view (left), and fabrication setup (right) © ICD/ITKE University of Stuttgart

1:1 Demonstrator

The ITKE – FibR demonstrator features a lightweight slab system composed of two engineered timber plates in combination with flax-fibre reinforced composite elements (Figure 9). In a typical ten-storey reinforced concrete building, the structure accounts for around 75% of the total weight, indicating that most of that material is required merely to support its own weight. The higher the building, the higher the percentage of total weight. The timber-flax-hybrid slab system addresses this issue by increasing the strength-to-weight ratio in the structure system through geometry and material system innovation. Through integrating the concept of widely-used lightweight suspended systems, the hybrid structure was able to direct forces through the fibre system mainly in tension, thereby increasing the global structural efficiency and reducing material usage and machining hours. The point-supported, multi-way spanning slab system was designed to explore the opportunities to break out from a grid system, allowing more freedom in architectural planning. The demonstrator showcases the mentioned aspects, especially as an integrated building component together with 3D-printed walls made from earth and cellulose.

Upscaling of a bio-material system

Upscaling natural-fibre filament-wound structures poses challenges in material capacity and fabrication efficiency. Due to the varying mechanical properties of natural materials, a multiscalar approach is necessary. The design method involves characterizing the material batch, analysing stress concentration at joints, and studying fibre interaction. Calibrations are performed at both material and component levels, considering material variety and fabrication inconsistencies through physical testing. Using natural fibres increases material usage and machining hours compared to synthetic fibres. To address this, the prototype explores integrating timber for efficient mass and volume construction where precise fibre directionality is less critical.

Figure 9. Prototype full view (left) and interface close-up (right) © Erik-Jan Ouwerkerk

Digitalization and standardisation

The project aimed to integrate research understandings of material, interface, and structure systems with fabrication considerations. The robotically-milled timber structure served as both the winding frame and the exhibition prototype, eliminating the need for additional steel frames (Figure 10). This approach enhanced geometric flexibility, enabling the fabrication of elements with varying sizes, depths, and anchor positions in a single setup.

Figure 10. Winding process(left), and timber milling process (right) ©ITKE University of Stuttgart © ICD/ITKE University of Stuttgart

New resolution of material optimisation

Structural topology optimization on fibrous structures necessitates re-evaluating material optimization through an understanding of fiber layups (interactions, passes, and angles) rather than individual fiber bundles. The use of natural fiber-reinforced composites introduces increased material usage compared to established fossil materials, leading to a shift in material optimization that considers not only minimizing structural weight but also incorporating structural redundancy at a higher degree and resolution. Additionally, the integration of total life cycle analysis and acoustic requirements highlights the need to go beyond material minimization when transitioning to biomaterial-based construction.

5. INTERFACING BIOBASED-MATERIAL SYSTEMS

The interfacing of different bio-material systems requires a deeper understanding of behavioural deviance under different environmental conditions and through/over time. Temporality and tolerance must be considered. Not only in the design and fabrication phase but also in terms of how the joints/interfaces could accommodate asynchronous changes after assembly.

5.1. MATERIAL INTERFACES - GAINING CONTROL OF TOLERANCES.

The Living Prototypes project explores three material interfaces: timber-to-fibre, fibre-to-earth, and earth-to-cellulose. The tolerances of each interface depend on the fabrication system and material quality control. 6-axis milling achieves a tolerance of 0.1 mm for timber plates, while coreless winding of fibre-reinforced composites can achieve a tolerance of 5 mm, influenced by the stiffness of the winding frame. To address interface deviation, timber is used directly as the winding frame to synchronize potential deformation. The relationship between plate deformation and timber-fibre ratio requires further investigation.

For connecting 3D-printed earth with timber-fibre-hybrid slabs, a plugged and tightened joint with higher tolerance was designed. However, the required tolerance exceeded the predicted clay shrinkage (Figure 11). During the drying process, the printed earth pieces shrunk approximately 12% with unpredictable deformation influenced by the heterogeneous mix, composition ratios, geometry, infill pattern, and environmental conditions. Upscaling the systems and associated mass may increase shrinkage and deformation. Consequently, a crack formed in one of the larger clay pieces supporting two slabs.

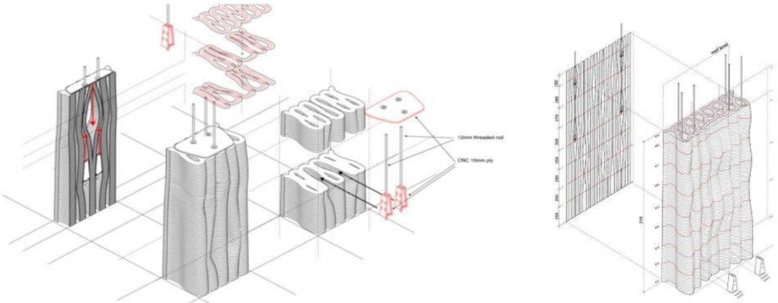

Figure 11. Interface detail between 3D Printed Earth and timber-fibre-hybrid slabs.

The earth-to-cellulose interface design utilized the processability of printed cellulose. After reaching the dry stage, the surface of the cellulose piece was post-processed to achieve the required planarity for the interface. Connection of the components involved embedding timber keys and screws in the earth wall, similar to the interface between brick masonry walls and window frames in traditional construction. Cavities were incorporated in the earth walls to secure and lock the connection keys at specific contact points (Figure 12).

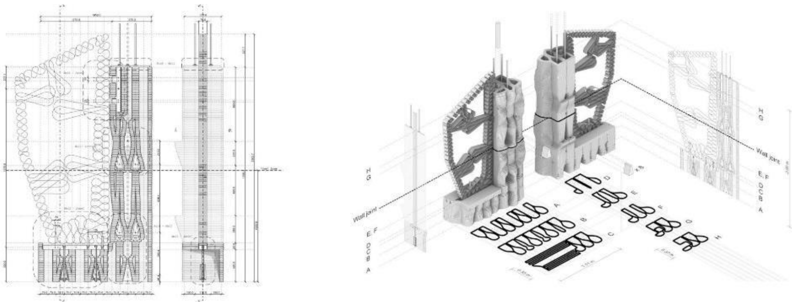

Figure 12. Interface detail between 3D Printed Earth and Cellulose screens.

5.2. TEMPORALITY IN FABRICATION OF BIOMATERIALS

Considering the temporal aspects of biomaterials in fabrication was crucial throughout the project. Initially, the plan was to 3D print prototypes on-site using locally-sourced materials with transportable manufacturing robots and large-scale printing equipment. However, logistical challenges, such as transport, setup, calibration, and long curing times with specific humidity conditions, made on-site production unfeasible. The curing times for cellulose and earth-prints range from two to three months depending on mass and require on-site storage for months before the exhibition. The slow progress of the printing processes due to material instability further hindered production speed. Well-controlled indoor climates are essential for quality and worker safety. A dry and temperature-controlled environment enables process control, predictability, and contributes to the health and safety of laborers.

5.3. CHANGE OVER TIME

Temporal aspects of bio-materials extend beyond the fabrication process and on-site installation, impacting interface deformation and long-term behavior. The growth, processing, and sourcing of bio-materials are influenced by local conditions, leading to heterogeneity and potential material shortages. Testing and adjustment are required for each batch of Flax fiber and printed earth, considering composition, climate, and machinery. Natural and reclaimed materials in the Biopolymer track vary based on source and batches, requiring consistent material selection. Components made of timber and 3D-printed cellulose experience dimensional changes due to humidity, while natural fiber-reinforced composites are affected by temperature, moisture, and UV exposure. Nonhomogeneous design and long-term drying of 3D-printed earth contribute to uneven crack propagation. Interface challenges arise from the need to accommodate material inconsistencies over time, necessitating flexible and adaptable connections to maintain desired mechanical properties.

6. OUTLOOK

The Living Prototypes project highlights the heterogeneity and temporality of biomaterials, demonstrating how digital techniques enable their incorporation in design and fabrication. These novel protocols and techniques challenge established practices in the building industry, but also bring opportunities for creativity and innovation. Working with biomaterials in a circular context requires resilient approaches to navigate complexities and adapt to changes in the supply chain and local conditions. The project emphasizes the need for deliberate cycles of reconstruction and user-participation in building processes. Future projects should explore long-term relationships with biomaterials, extending partnerships beyond design and fabrication to service-life, inhabitation, and reconstruction. Sustainability remains a key challenge, as architecture can address social and environmental sustainability through the use of biomaterials.

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AUTHOR CONTRIBUTION

Tamke, M.: Project Lead, Funding acquisition, Investigation, Methodology, Writing -Original Draft, Writing - Review & Editing , Chen, Tzu-Ying: Investigation, Writing -Original Draft, Carrasco, O.: Investigation, Writing -Original Draft , Ryan, Á., Bouchi, D.: Investigation, Methodology, Funding acquisition, Writing -Original Draft, Ramsgaard Thomsen, M.: Investigation, Methodology, Ressources, Writing - Review & Editing, Nicholas, P.: Investigation, Methodology, Writing - Review & Editing, Dubor, A.: Investigation, Methodology,, Writing - Review & Editing, Cabay E.:Design, Visualization, Writing - Review & Editing, Bangsgaard, A.: Investigation, Writing - Review & Editing, Dörstelmann, M.: Investigation, Writing - Review & Editing, Naldoni, L.: Investigation, Writing - Review & Editing, Markopoulou, A.: Ressources, Writing - Review & Editing, Knippers, J.: Investigation, ressources Writing - Review & Editing.

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