Living Prototypes - Digital Fabrication With Biomaterials

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Digital Fabrication With Biomaterials

Living Proto Types

THE AEDES METROPOLITAN LABORATORY

ANCB

Edition #7

LIVING PROTOTYPES

DIGITAL FABRICATION WITH BIOMATERIALS

ANCB EDITION #7

Project Team
3D-Printed Earth
University partner
IAAC – Institute for Advanced Architecture of Catalonia, Barcelona, Spain
Industry partner
WASP, Massa Lombarda, Italy

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

Bioplastic Prints
University partner
CITA – Centre for Information Technology and Architecture, Royal Danish Academy, Copenhagen, Denmark
Industry partner
COBOD International A/S, Copenhagen, Denmark

Research Coordinator and Curator
ANCB The Aedes Metropolitan Laboratory, Berlin, Germany

Partner
BSSR – The Federal Institute for Research on Building, Urban Affairs and Spatial Development, Bonn, Germany

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Symposium
9 December 2022
ANCB The Aedes Metropolitan Laboratory, Berlin

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Living Prototypes

Digital Fabrication With Biomaterials

Living Prototypes was an ANCB research project on digitally fabricated building components for living spaces with bio-based materials, that were developed over 18 months by three teams of university and industry partners from Denmark, Germany, Italy and Spain. It was funded by the *Zukunft Bau* programme of the German Federal Ministry for Housing, Urban Development and Building and culminated in an exhibition at Aedes Architecture Forum in 2022–23.

Introduction

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Vision

Project Team

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duction

Preface

Hans-Jürgen Commerell and Kristin Feireiss

Directors, ANCB The Aedes Metropolitan Laboratory

What might our homes look and feel like if they were built without fossil fuels? How can we advance the use of biological and recyclable building materials? What beneficial change can digital fabrication and prototyping bring to both architecture research and to communicating knowledge about construction and design processes? These questions were at the core of the *Living Prototypes* project.

It is a well-known fact that the building sector contributes significantly to the accelerating climate crisis and the depletion of the earth's finite resources. At the same time, unabating population growth and urbanisation require more homes and thus more construction, using more materials and producing more emissions. In response to these challenges, *Living Prototypes* proposes collaboration, research and visions. On how we can tackle challenges if we work together across disciplines and borders, between research and industry; on how our built environment could be if we design and build with better resource efficiency and with regard for the life cycles of materials; and on creating a new mind-set regarding the quality of our living environments and the way we engage with them.

Living Prototypes was a 1.5-year European research project, funded by the *Zukunft Bau* programme of the German Federal Ministry for Housing, Urban Development and Building and coordinated by ANCB The Aedes Metropolitan Laboratory. University institutes in three countries each collaborated with an industry partner on developing bio-based materials in architecture to digitally fabricate 1:1 scale prototypes of building components for everyday living spaces.

The project innovates on several levels. It advances the potential of digital fabrication in architecture with regard to energy and resource efficiency by exchanging conventional, fossil-based materials with natural, bio-based materials. It goes beyond the environmental aspect of sustainability to explore its socio-political dimension by making the potential of digital production for architecture tangible and conceivable. And it scales up cutting-edge research out of the lab and into a 1:1 scale prototype that we can exhibit at Aedes. It captures our collective imagination by showing the change these building materials could bring to the most recognisable space for all of us: our everyday living space.

The three research teams were:

3D-Printed Earth	IAAC – Institute for Advanced Architecture of Catalonia, Barcelona WASP, Massa Lombarda
Flax Fibre-Winding	ITKE – Institute of Building Structures and Structural Design, University of Stuttgart FibR GmbH, Kernen
Bioplastic Prints	CITA – Centre for Information Technology and Architecture, Royal Danish Academy, Copenhagen COBOD International A/S, Copenhagen

The outcomes of the *Living Prototypes* project are exhibited at Aedes Architecture Forum in Berlin from 9 December 2022 until 25 January 2023, and discussed in a symposium on the day of the opening as well as in this publication. In the exhibition, a 1:1-scale installation set in a typical floorplan of a one-bedroom apartment brings together the three separate prototypes. Contextual and supporting information includes visions for how biomaterials and digital fabrication methods might encourage a change in how we build and live in the future, as well as reflections on designing with bio-based materials and examples of further prototyping explorations by each research team.

At Aedes and ANCB, we have more than 40 years experience in the communication of architecture; at bringing to light emerging ideas, showing these in our exhibition space, presenting them in publications and discussing them on our discourse platform. At the core of the *Living Prototypes* project is the task of translating abstract laboratory explorations into something physically tangible and recognisable that helps us – the public – as well as the building industry and policy-makers to imagine the spaces and architecture that these new materials and digital construction techniques make possible. In essence, it is about providing impulses that can convince and create political pressure to innovate. We strongly believe in the role of exhibitions as catalysts of change.

Living Prototypes builds on ANCB's 2017 discussion series *Craftsmanship in the Digital Age. Architecture, Values and Digital Fabrication.* It responds to the series' conclusions by supporting the transfer of advanced research from the laboratory to architecture practice, by demonstrating how digital technologies enable the building industry to switch to resource-efficient building materials and construction, by stimulating a digital building culture, and prompting further exploratory applications of digital fabrication in the sustainable construction, use and maintenance of buildings.

Crucially, *Living Prototypes* continues the collaboration with the BBSR that was started with *Craftsmanship* and I would like to thank the BBSR most sincerely for their support, and especially Helga Kühnhenrich and Arnd Rose for their dedication and their visionary thinking.

We would also like to thank the projects' advisory board, who with their diverse expertise stimulated many directions of thought and helped us frame the research more holistically. You can find their names on page 64.

Most of all, my sincere thanks go to the teams from Copenhagen, Stuttgart, Barcelona and Massa Lombardo for their unrelenting research spirit, their commitment, their creativity and their sense of humour. During the course of *Living Prototypes* lives changed, babies were born – one in each team! – members moved on to different projects and others joined the *Living Prototypes* family. There is no space here to name all of them. Please turn to page 60 for the teams' profiles and names.

Finally, we would like to thank our project curators Dunya Bouchi and Áine Ryan and the entire team at Aedes, especially Christine Meierhofer, Hanna Düspohl and Christian Thomas, who make everything happen.

Foreword

Helga Kühnhenrich and Arnd Rose

BBSR – The Federal Institute for Research on Building, Urban Affairs and Spatial Development

We are living in times of challenges that demand changes. And we are living in spaces that embody these challenges, while the changes are yet to be committed to. Over the past few years, social awareness of the need to reduce our anthropogenic footprints has grown; in terms of carbon dioxide emissions, resource consumption and waste production. Considering that today around 40% of the total CO_2 emissions in Germany are related to the construction, use or dismantling of buildings, it is clear that there is still a long way to go before the objective already established by law is met: a climate-neutral building stock by 2045. At the same time, it must be ensured that building and housing remain affordable in the future. When thinking about how to achieve these objectives with well-known solution-strategies developed for either one or the other, their conflicting agendas quickly become apparent: it seems to be a paradoxical task of achieving more (in terms of CO_2 savings, sustainable and affordable housing) with less (in terms of building materials, time and money).

The need to go beyond those well-known strategies is obvious. Put simply, new solutions have to evolve faster than new crises. While there is certainly no such thing as a single 'quick fix', there are many areas in which to start. For example, by using new digital possibilities to rethink materials and processes in conjunction with typologies, an integral – and non-paradoxical – approach can be developed.

INTRODUCTION

In 2017, ANCB The Aedes Metropolitan Laboratory launched the discussion series *Craftsmanship in the Digital Age* in collaboration with the Netherlands Embassy in Berlin, NOWlab and the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). This explored the implications and perspectives of digital fabrication for the construction sector. With the *Living Prototypes* project a follow-up step is taken, from a theoretical discourse to an experiment that the audience can see, touch and discuss.

Research provides many promising proposals, but there is always a risk that the results will remain in the ivory tower or disappear into the drawer. To avoid this, it is essential to build a bridge between the latest scientific findings, their translation into practical applications and their communication to a broad audience. Therefore, one of the aims of the *Living Prototypes* project was to provide such a bridging space, where ideas could be joined to solve a common task: to build a full-scale prototype that demonstrates the potential of natural and bio-based recycled materials in combination with the latest techniques in digital fabrication.

Three interdisciplinary and international teams took up this challenge, and it has been a pleasure to follow how they have brought together their different ideas and perspectives. In a way, their collaboration is a prototype in and of itself: a continuous chain of interlocking processes from digital design to digital manufacturing, connecting the knowledge of experts throughout Europe.

The result is a truly visionary suggestion of what resource-conscious building and living could look and feel like in the near future. As three physical prototypes interconnected to form a living space, they can be experienced, discussed and enhanced. This is exactly why the German federal research programme *Zukunft Bau* is supporting this project about new ways of building and material-efficient design. The prototypes demonstrate the current state of applied scientific knowledge and experimental practice. They don't stand for a finished proposal, but rather illustrate new concepts and make it possible to examine their suitability and acceptability for wider practice.

Figuratively speaking, the *Living Prototypes* project is a step off the beaten track. For us at the BBSR, it is steps like this that mark a new path. And in these times of challenges, new paths surely are needed if we want to reach our goal to change how we build and live in the short amount of time available!

Research Frame

Martin Tamke
Research Coordinator, CITA – Centre for Information Technology and Architecture

Bio-based Materials and Architecture

The building industry is dependent on fossil fuels. Industrialisation brought about a paradigm of cheap mass-production with an almost total reliance on carbon-intensive materials and processes. Practised globally, this contributes massively to the overconsumption of the earth's resources – we are literally depleting the earth. A change from a practice of extracting materials from the geosphere to a practice of generating materials in harmony with the geosphere is urgently needed.

Industrial techniques and technologies developed in the Global North are today employed all over the world. Using the exact same set of materials from the geosphere, they cause pre-existing building cultures to be sidelined and urban and building typologies to be carbon copied to all corners of the world. By maximising industrial strategies of scale and standardisation they level local differences in terms of material sources, local climates and available human skills, and in so doing achieve a homogeneous outcome. They provide global access to durable materials, which are at least on an entry level simple to work with and easy to replicate, leading to an abandonment of local crafts and material complexities.

All of this happens because we neglect the environmental, climatic and social impacts of these global building practices. They are based on a linear path of extraction, refinement, building and operation; followed by an end-of-use scenario where materials are considered waste and reuse or recycling presents enormous challenges. The refinement of the raw materials into the homogenous state required for this global building practice needs vast amounts of energy and produces mountains of waste.

Today the broader context in which we build is being recognised. It is obvious now that the basis of construction has to change from a practice of extraction that depletes limited raw materials, to a practice using regenerative materials in a circular manner.

A bio-based material paradigm

A shift towards a bio-based material paradigm in the building industry is overdue. A shift from the use of materials that come from the geosphere to materials that stem from the biosphere. These include living organisms such as mushrooms, mycelia or bacteria. Bio-based materials are grown and harvested, they are processed, designed and graded.

The bio-based material paradigm shift will be fundamental. A mere swap of one material for another is not a possibility anymore, as this does not alter the current logic of endless growth. Instead, an awareness of limits on the part of the building industry is necessary, even in the face of the urgent need for new and better homes for a growing global population. Bio-based materials are naturally limited by the amount of sunlight, phosphorus, carbon dioxide, etc. The practical consequences of these true limits are radical and shape any future building practice.

Biological materials are rooted in local cultures where the knowledge to process and build with them has been established over thousands of years. These processes are intrinsically linked to manual labour and craftsmanship. The computational architecture community to which the *Living Prototypes* teams belong, investigates how these traditionally manual processes can be transferred into digital techniques. Design and fabrication with biomaterials need to follow material logics rather than constraints that are predominantly formal or geometrical.

Biomaterials are also inherently heterogeneous, and often have very strong material behaviour. How to move from a building practice based on standardised, homogeneous and high-strength materials, to one based on potentially weaker, ideally unprocessed materials? The research underlying the *Living Prototypes* exhibition uses high-tech in order to work with low-tech materials. The CITA – COBOD research team uses IOT sensing and prediction, based on machine-learning, to model the material behaviour of bio-plastics during processing and use in a building component. The IAAC – WASP team developed methods to refine local earth in a way that can be 3D-printed at the building scale. The ITKE – FibR team developed material testing, computational design and simulation techniques that enable the design of ultra lightweight constructions with flax; a natural fibre that has been cultivated for thousands of years, but only recently discovered for technical use. Thus, all three exhibited prototypes step beyond the laboratory to explore how these biomaterials can be employed at the architectural scale and impact everyday spaces.

Lastly, all biological materials have life cycles. They come to life, grow, but also die and decay. How can each of these temporary states become a part of architectural thinking? How can building practice move from preventing decay to embracing this very nature of biomaterials in a way that supports architecture?

New thinking and new ideals for architecture

The shift to a bio-based material paradigm represents a fundamental turn in architecture. This profession has been obsessed with the permanent – even though it is well known that most buildings are torn down relatively quickly. The temporality of architecture needs to be understood and embraced. It must be represented in the drawings and models that inform building at all stages.

New architectural ideals that support constant change and adaptation are needed, be that adaptation to the deterioration of natural materials or to changes in the function of a building. The material systems shown in the *Living Prototypes* exhibition can, in comparison to the dominant building materials today, be adapted and reused with less energy usage. These new ideals need to include the social level, to engage the inhabitants at the scales of the building or the city. Any shift in building technology and material needs to be envisioned through the perspective of the user.

These questions underlying the *Living Prototypes* project demonstrate how digital building techniques can enable the building industry to make the overdue shift towards natural, biodegradable and recyclable materials. The research conducted within *Living Prototypes* supports this endeavour by developing new processes with biomaterials and by producing a combined prototype. This joint prototype is a manifestation of the architectural research method shared by all partners in the *Living Prototypes* project. That is to move continuously from probes to prototypes and to large-scale demonstrators in order to evaluate ideation, speculation, specification and finally fabrication and use.

Curatorial Statement

Dunya Bouchi and Áine Ryan

Curators, ANCB The Aedes Metropolitan Laboratory

Living Prototypes encourages a change in architectural thinking by presenting a 'proof of concept' that can stimulate political and societal desire to innovate the ways we build and live. To describe this change, the ideas and outcomes generated by this research project are collated under the themes of *Materials, Prototypes and Visions*, both in this publication and in the *Living Prototypes* exhibition.

Materials (16–35)

The design of the prototypes connected the process of developing biomaterials from earth, flax and natural cellulose, with the process of crafting these into building components at the 1:1 scale: by exploring how to treat and combine raw materials, identifying the appropriate digital fabrication techniques, and examining how the test results performed structurally, behaviourally and aesthetically.

Prototypes (36–43)

The three separate prototype building components – an earth wall, a cellulose screen, a flax fibre slab – could be integrated as a mini building system, despite having different logics of material and making. Bespoke joint detailing was fluently incorporated as an iterative refinement of the prototype design, just as it can to support other building functions and individual user needs.

Visions (44–57)

A committed uptake of biomaterials in the building industry can transform how architecture is designed and built; by guiding the ideals of architectural design towards more resource-conscious and holistically sustainable building practices, and by overhauling long ingrained models and attitudes around collaboration and innovation across the industry.

Perhaps, most fundamentally, *Living Prototypes* is about collaboration. It expands on existing collaborations by bringing together the interdisciplinary, practice-focussed ANCB network with the teams' research network. Within the project framing and against the backdrop of the pandemic, the geographically dispersed research teams – just like the different materials and the different fabrication methods – found their own collaboration language. These teams were:

3D-Printed Earth

IAAC – Institute for Advanced Architecture of Catalonia, Barcelona;
WASP, Massa Lombarda

Earth is a traditional and inexpensive building material, for which extensive knowledge exists. IAAC and WASP employ 3D printing and computational design to improve the structural and climate-regulation performance of earth constructions. This also enables a new flexibility in the architecture achievable with this biomaterial, advances its aesthetic capacity and makes the construction process more efficient and feasible for infill and other forms of built environment densification.

3D-printed earth wall with opening

Flax Fibre-Winding

ITKE – Institute of Building Structures and Structural Design, University of Stuttgart; FibR GmbH, Kernen

Robotic coreless fibre-winding aims to optimise material efficiency in architectural components by avoiding formwork and material cutoffs. Material use corresponds to structural demands. ITKE and FibR investigated robotic coreless fibre-winding using natural flax fibres. Through the inter-material dialogue with other living prototypes at the Aedes exhibition, the project communicates the relevance of such material systems in future living spaces.

Robotic winding of flax-fibre ceiling

Bioplastic Prints

CITA – Centre for Information Technology and Architecture, Royal Danish Academy, Copenhagen; COBOD International A/S, Copenhagen

Bioplastics are renewable, inexpensive, biodegradable and chemically diverse. Digital data analysis technologies, such as machine learning, make it possible to predict and control the behaviour of these complex materials during and after the printing process. CITA and COBOD prototyped components for interior spaces using two complementary bio-based materials. These suggest future circular material life cycles in buildings that are made possible by this adaptive manufacturing process.


3D-printed cellulose panels interlocked as screen

As the exhibition demonstrates, not only did the research teams achieve the aim of building 1:1 scale prototypes, they took a further research step to suggest how the prototypes might be combined into a novel building system. This only hints at the possibilities achievable by more embedded R&D in building practice. Many Master and PhD level students were involved in all the teams, showing how the next generation of architects becomes increasingly familiar with this technological knowledge and know-how.

The change in the way we design, build and live as encouraged by this project is timely. Not only because of the urgent climate crisis, but also because the full potential offered by biomaterials and digital fabrication has not yet been sufficiently evaluated across the building industry. Room for experimentation of this kind is needed. So, too, is a critical discourse on the shift in values required to guide how we build from now on. *Living Prototypes* intends to stimulate this discourse.

Mate

rials

The design of the prototypes connected the process of developing biomaterials from earth, flax and natural cellulose, with the process of crafting these into building components at the 1:1 scale; by exploring how to treat and combine raw materials, identifying the appropriate digital fabrication techniques, and examining how the test results performed structurally, behaviourally and aesthetically.

3D-Printed Earth

IAAC – Institute for Advanced Architecture of Catalonia, Barcelona

WASP, Massa Lombarda

Although the earth material comes directly from the ground, the printed mix is carefully composed to control the quantity of clay and the addition of components such as natural fibre and enzymes.

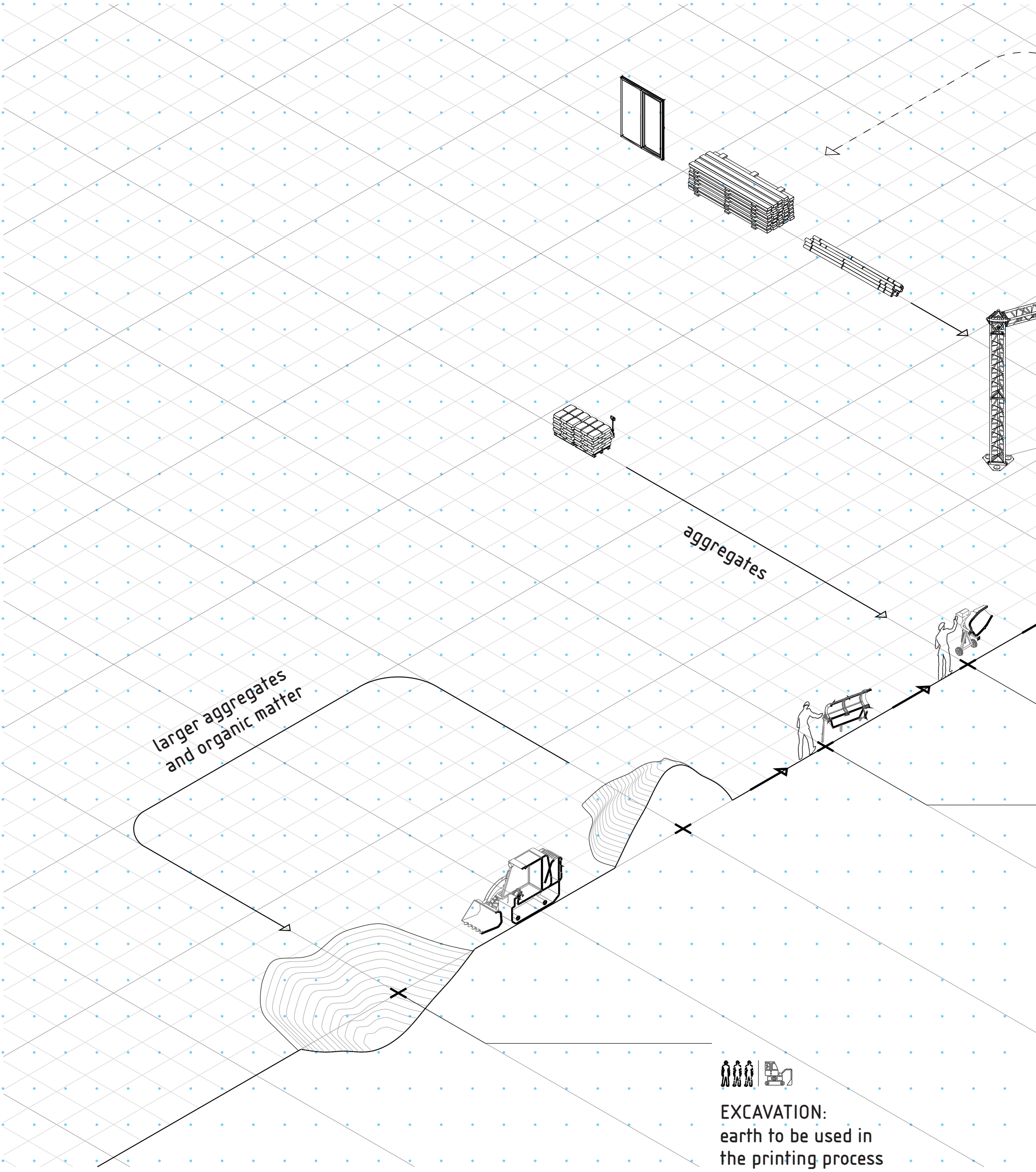
IAAC and WASP employ 3D printing and computational design to improve the structural and climate-regulation performance of earth constructions. This also enables a new flexibility in the architecture achievable with this biomaterial, advances its aesthetic capacity and makes the construction process more efficient and feasible for infill and other forms of built environment densification.

The first phase of the project, developed with the 3D Printing Architecture Programme (3DPA) at IAAC, produced a housing prototype of nine square metres at the IAAC Valldaura Labs campus.

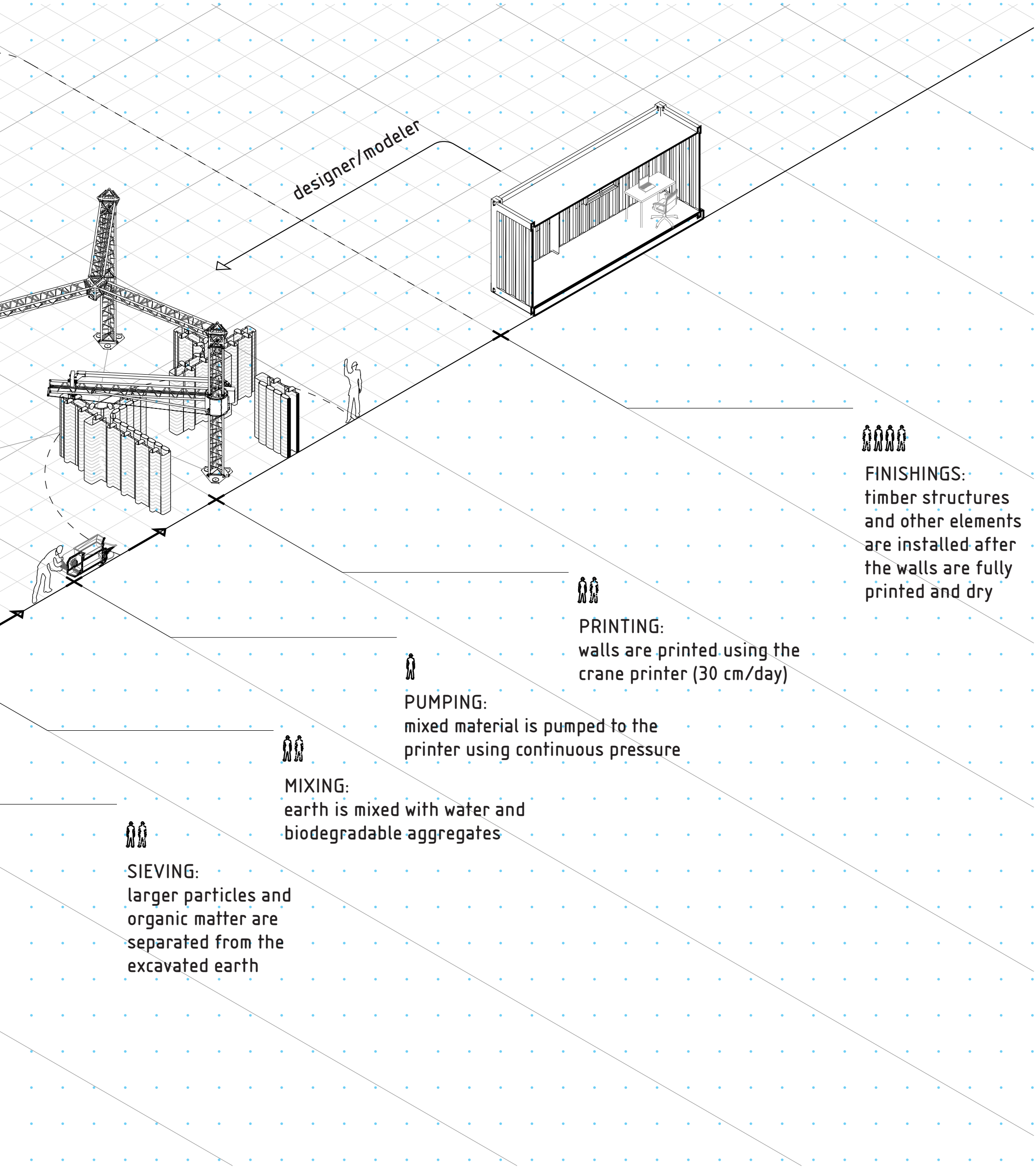
Building on this research, the focus of the final prototype was the demonstration of the fine detailing possible with 3D printing, as well as the specific material qualities obtainable when addressing performative and cultural questions of housing.

30cm per day of wet earth are extruded onto the printed wall. Drying takes several days and determines the rhythm of the printing process.

MATERIALS

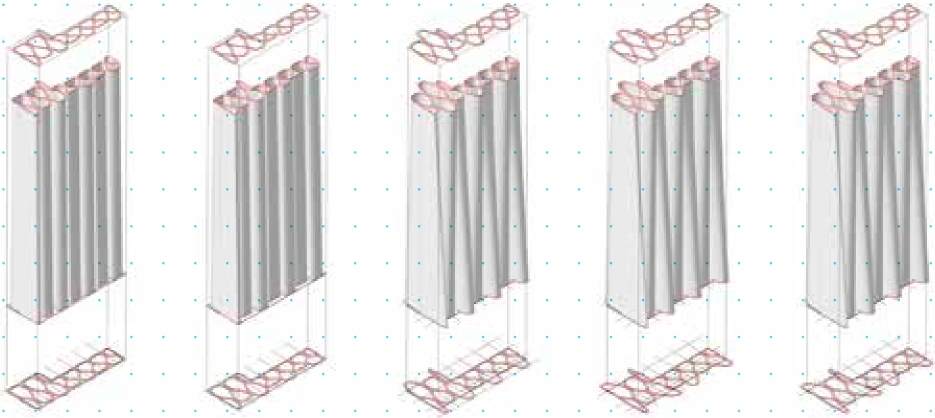


EXCAVATION:
earth to be used in the printing process is excavated within 2km of the site



Zero kilometre full cycle from the extraction of the earth material to the printing of a building

MATERIALS



Working digitally with parametric design enables the easy exploration and evaluation of design solutions to site conditions, such as self-shading from sun.

The entire project is built in one go, layer by layer. Building on-site ensures a seamless process between material extraction, preparation and printing of the building.

TOVA, the first earthen 3D-printed building in Spain, was printed by the students of the 3DPA programme over six weeks in February 2022.

The architectural design possibilities are determined by the nature of the construction site and by understanding the limits and possibilities of each 3D printer.

Flax Fibre Winding

ITKE – Institute of Building Structures and Structural Design, Stuttgart
FibR GmbH, Kernen

The raw material flax is a fibrous entity.

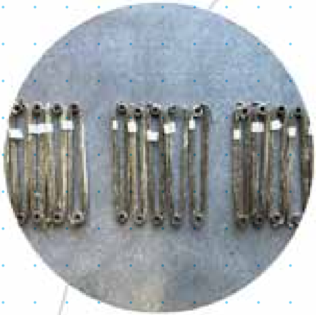
Research into natural fibres at ITKE explores the structural and design potentials of coreless-wound fibre reinforced composite structures. Building on previous research for the *Maison Fibre* and the *livMatS Pavilion*, this project optimises the material efficiency of a lightweight hybrid slab system, by integrating timber into the natural fibre system. During the first phase of the project, the research focussed on the material system build-up. The structural performances under weather exposure of natural fibres impregnated with various bio-based resins were researched and tested.

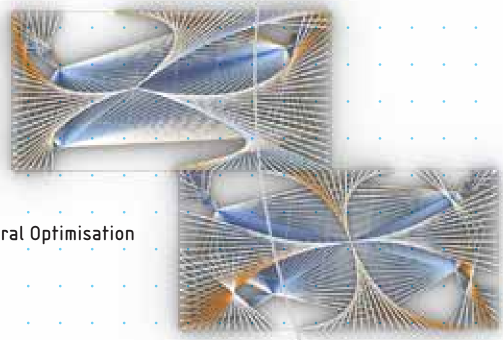
The hybrid structural system and material interfaces were further developed by re-studying the material allocation in the system and maximising the use of fibres under tension. This led to the development of a lightweight hybrid slab system, combining flax fibres impregnated with bio-based resin and a 19mm three-layer timber plate. Given the adaptability of the fibre syntax, mass customisation of the slabs with varying supporting conditions could be achieved.

Robotic fibre-winding fabrication works with flax fibres prepared as yarns.

MATERIALS

Material Structural Tests



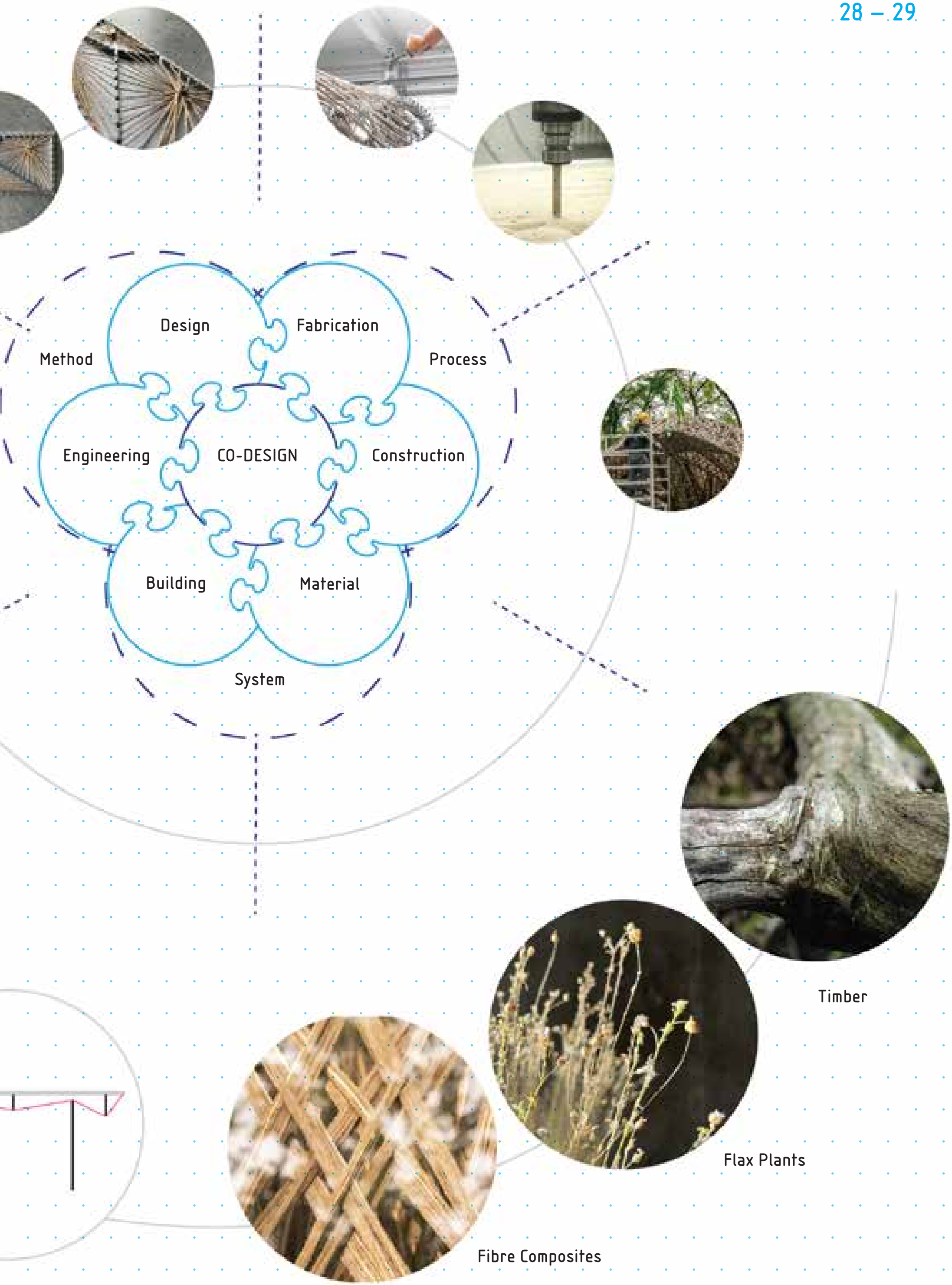


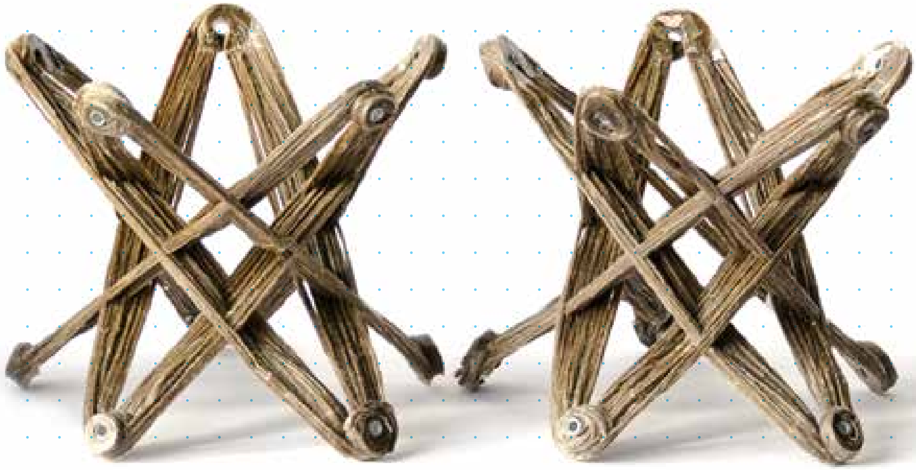
Syntax Structural Optimisation

Building System

Structural System

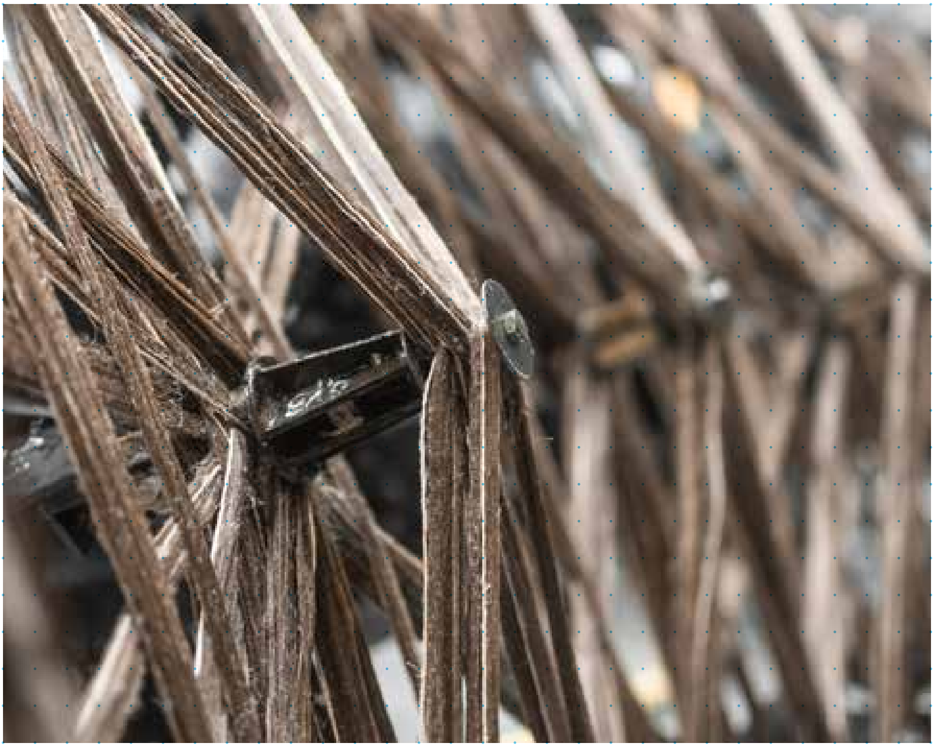
A co-design research framework used to generate the robotic fibre-winding integrated systems


Design
Fabrication
Method
Process
Engineering
CO-DESIGN
Construction
Building
Material
System
Timber
Flax Plants
Fibre Composites



Star-shaped specimens testing the mechanical properties of the material system

Resin-impregnated flax bundles



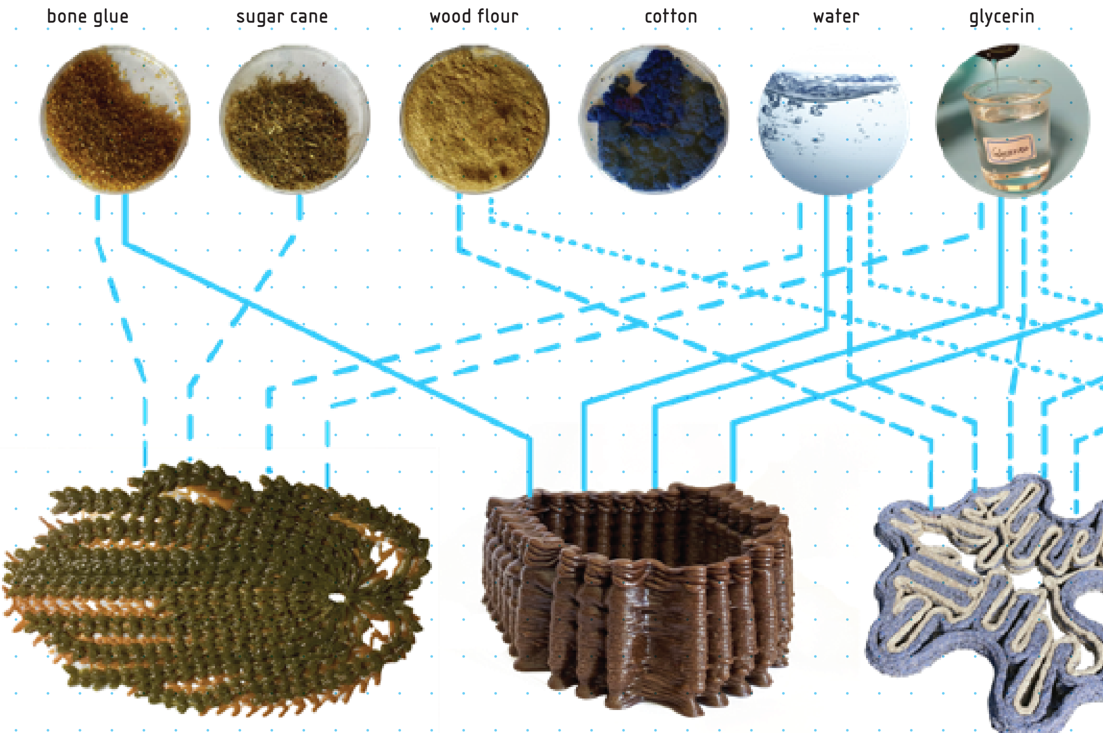
Connection detail of the 2021 ITKE project LivMats Pavilion

Robotic filament winding of flax fibres onto composite ceiling panel

Bioplastic Prints

CITA – Centre for Information Technology and Architecture, Copenhagen

COBOD International A/S, Copenhagen



BioPolymers for 3D printing: variation in type and amount of a small set of all-biological and often recycled materials allows to print elements with a wide range of performances, such as: colour, strength or elasticity.

CITA and COBOD use adaptive manufacturing processes with bioplastics to explore component-based assemblies for interior spaces. As this type of material is 'designed', its performance can be continuously specified to meet requirements using strategies of material grading. In the research, two bioplastics were developed and applied in two different prototypes.

In the 'organic' strand, with a cellulose and Xanthan-based slurry, the team scaled existing small-scale robotic printing at CITA to large-scale gantry-based production at COBOD usually used for 3D concrete printing. The printed cellulose screens are higher than a person. They offer a new material expression with a surprisingly fine structure. The cellulose based biopolymer consists of 70% water during printing. This needs to evaporate in the subsequent curing process, during which the material shrinks by 20% to 30% in a seemingly uncontrollable way. In order to determine the final shape of the pieces pre printing, all printed pieces were closely monitored and the resulting data was used to develop a predictive system using machine learning.

The biopolymer raw material is mixed pre-printing with common construction tools.

MATERIALS


The cellulose and Xanthan-based slurry can be processed by large-scale concrete printers such as the COBOD printer which has a printing range of up to 20m × 24m.

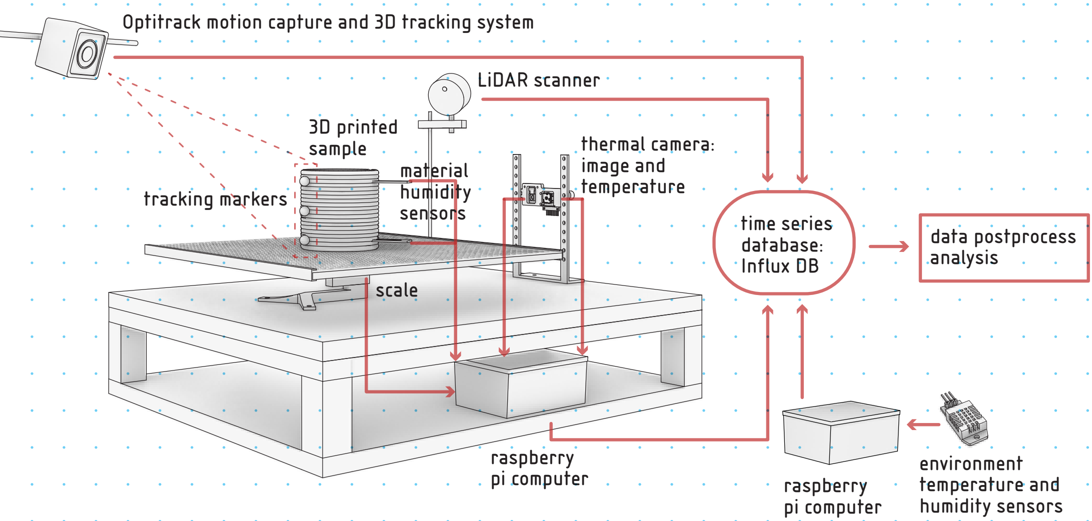
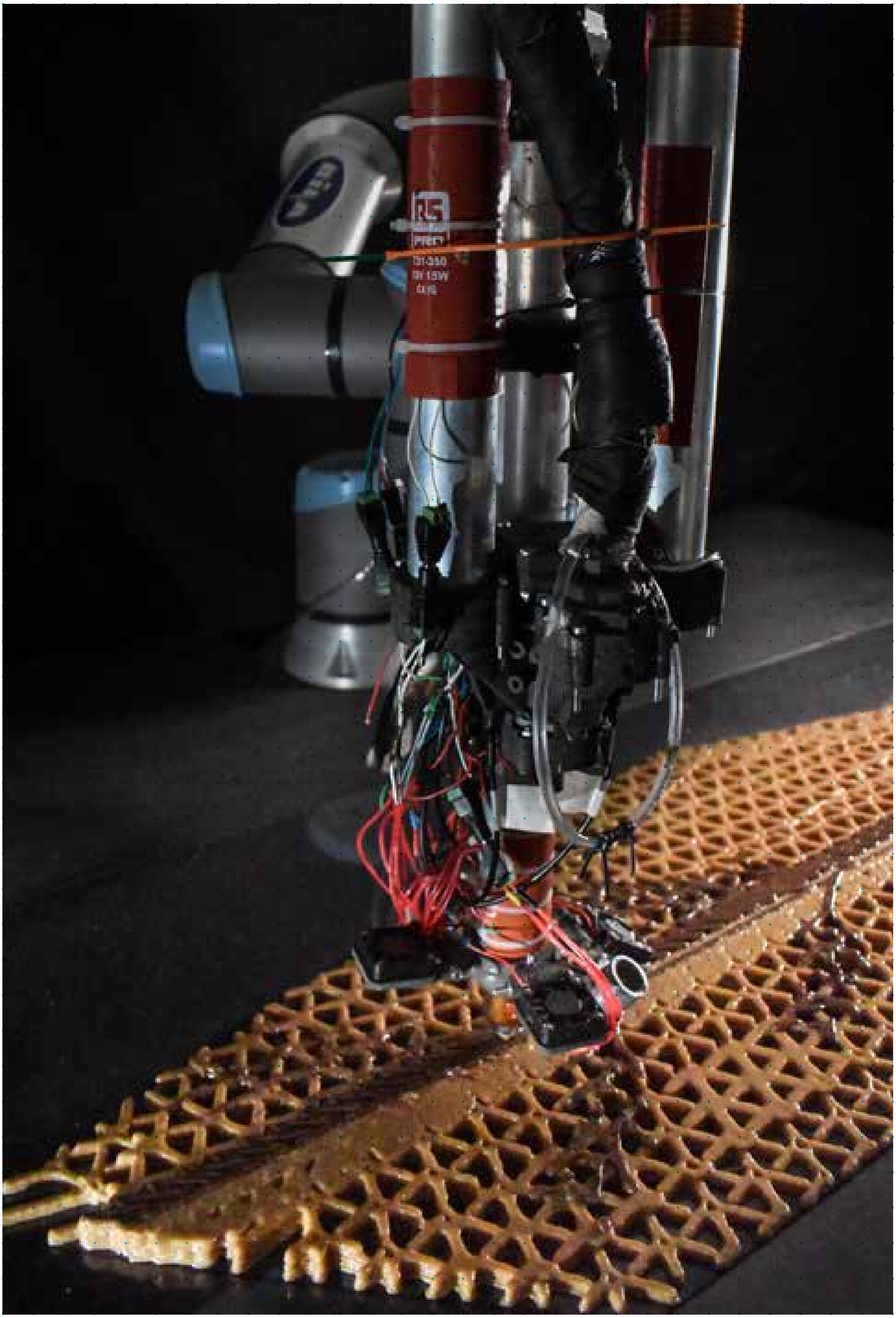


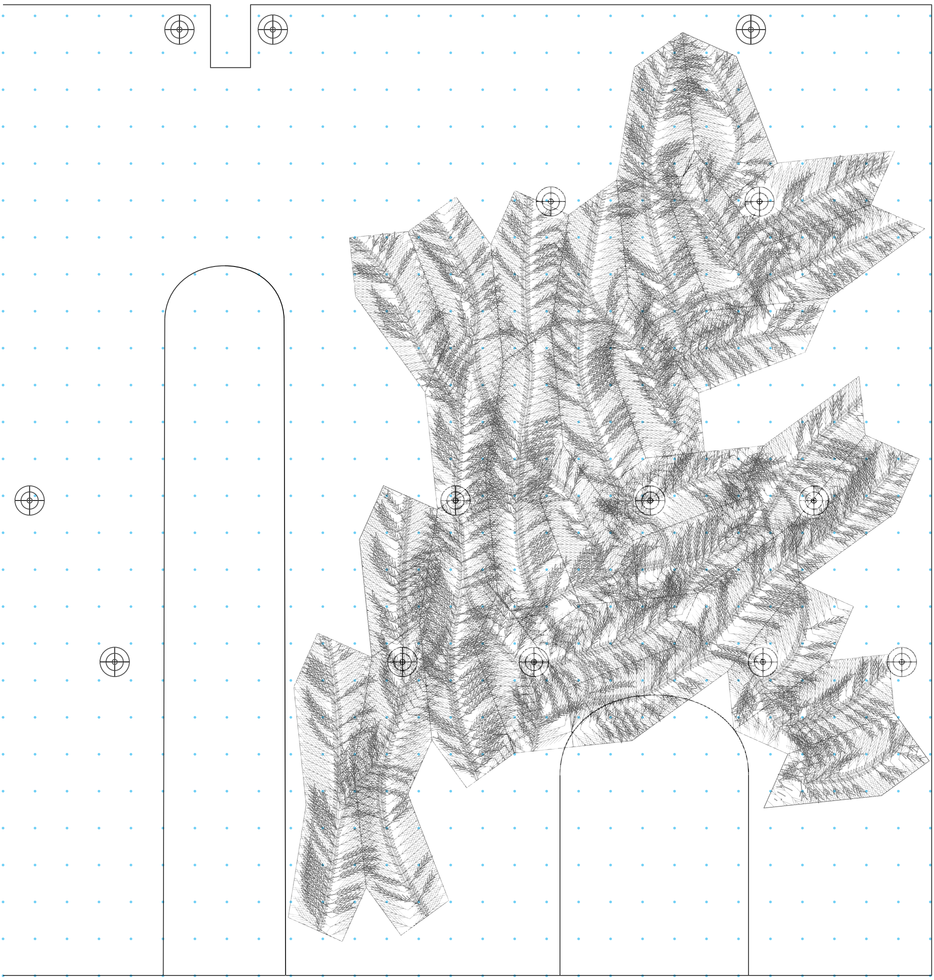
Diagram of the developed sensor setup to measure the change of the prints and the environment over time, tracking humidity, temperature and shape.

The biopolymer screens printed at COBOD are 2.3m high and weigh 35kg each.



Printing of bone glue panels with a custom-made printing head that can blend up to three base materials. In order to be fluid and printable, bone glue needs to be handled at 60° C.

In the 'animalic' strand, the investigation of the printing and grading of bone glue-based bioplastics led to the production of a six metre-high wall-panelling system that was installed in the exhibition. The addition and blending of fillers such as bark, cotton or seagrass to the bone glue altered the performance and colour of the printed panels. A custom-made robotic printing head together with special control software developed by CITA and machine learning strategies, allowed computational architects from CITA and bio-engineers from the Technical University of Denmark to identify the most workable mixes for printing individual panels of up to two metres in size.



The bone glue wall-panelling prototype was informed by the features of the Aedes exhibition space wall.

Proto

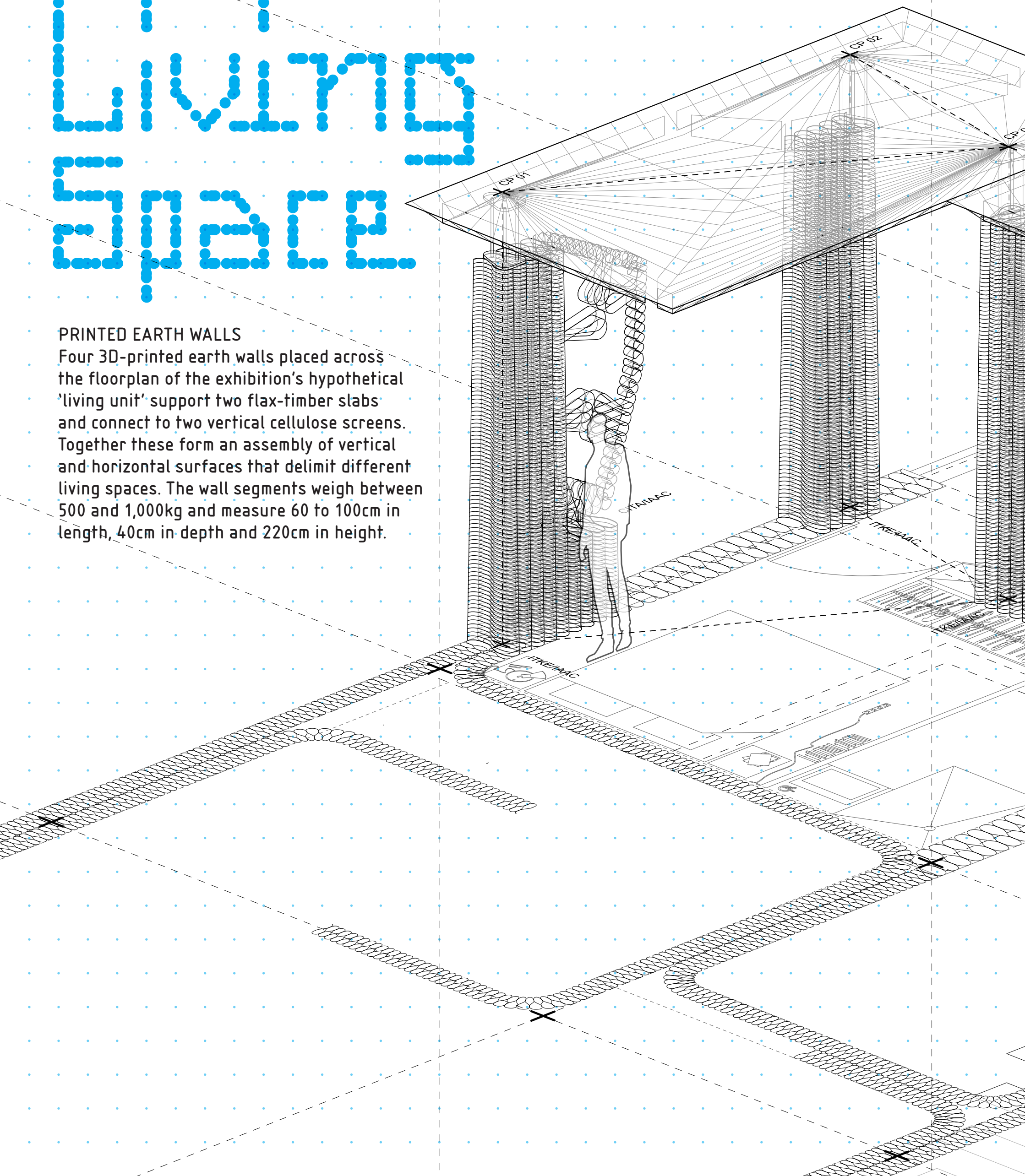
types

THREE PROTOTYPES – ONE APPLICATION

The three separate prototype building components – an earth wall, a cellulose screen, a flax fibre slab – could be integrated as a mini building system, despite having different logics of material and making. Bespoke joint detailing was fluently incorporated as an iterative refinement of the prototype design, just as it can to support other building functions and individual user needs.

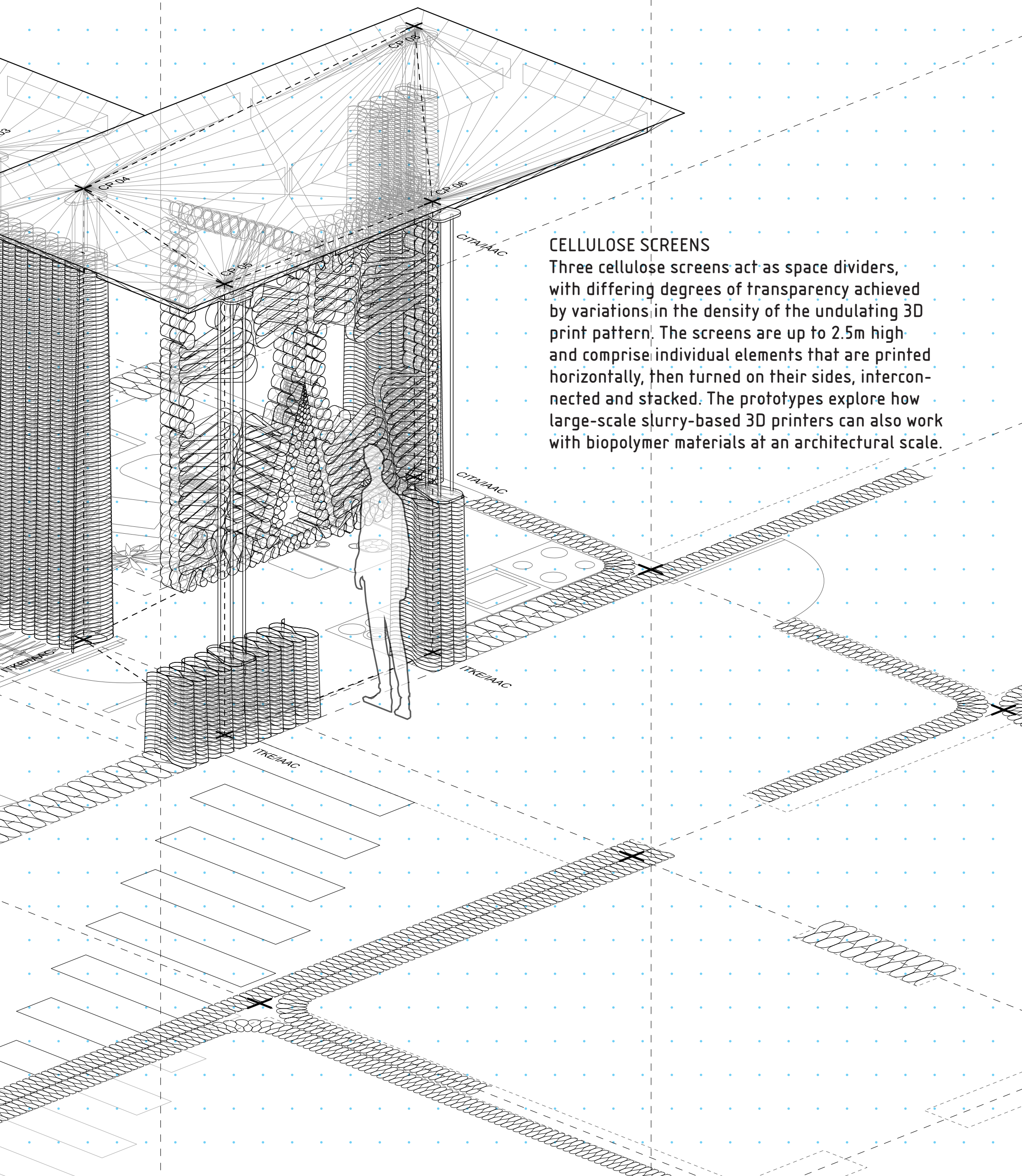
A Biomaterial Living Space

PRINTED EARTH WALLS
Four 3D-printed earth walls placed across the floorplan of the exhibition's hypothetical 'living unit' support two flax-timber slabs and connect to two vertical cellulose screens. Together these form an assembly of vertical and horizontal surfaces that delimit different living spaces. The wall segments weigh between 500 and 1,000kg and measure 60 to 100cm in length, 40cm in depth and 220cm in height.



FLAX FIBRE SLAB

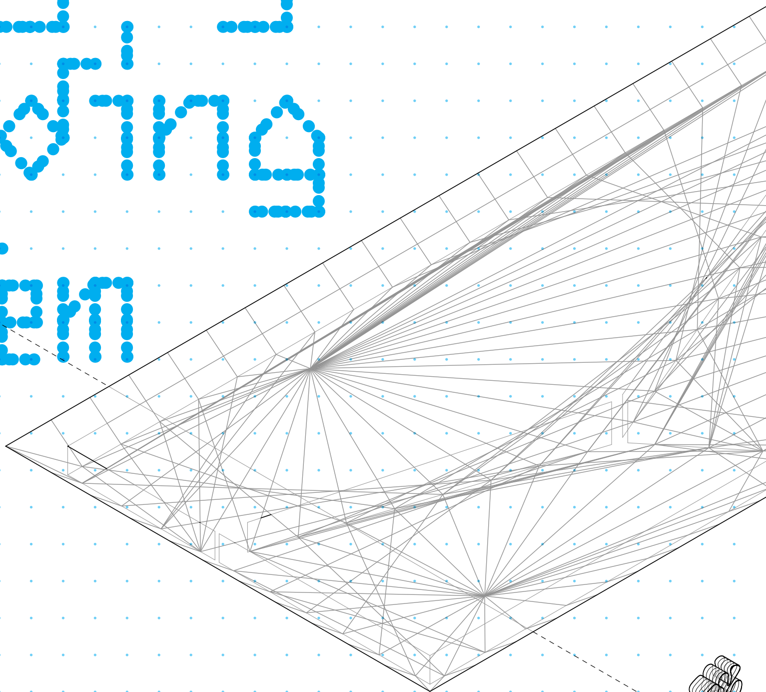
The two flax-timber hybrid slabs are point supported by the printed earth walls at different positions, thereby demonstrating the potential of the hybrid system to easily adapt the structural design to give increased design freedom for the floorplans of a living space. Both slabs are four metres long, two metres wide and weigh approximately 200 kg.



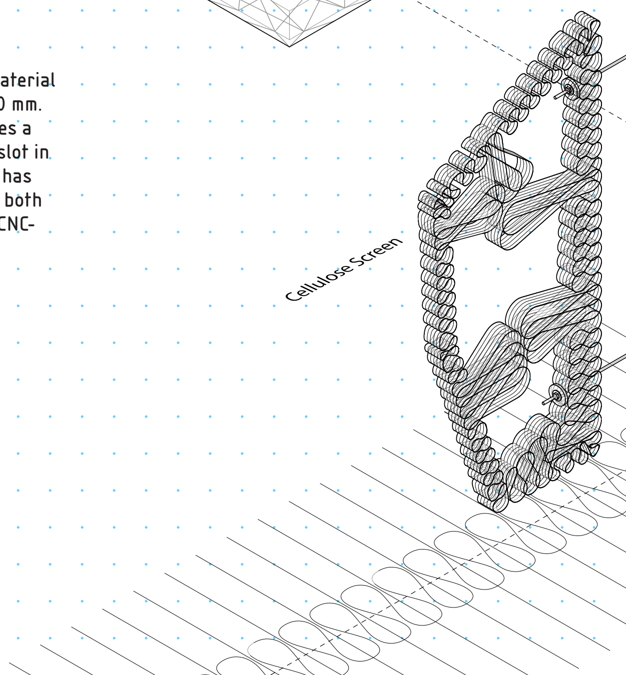
CELLULOSE SCREENS

Three cellulose screens act as space dividers, with differing degrees of transparency achieved by variations in the density of the undulating 3D print pattern. The screens are up to 2.5m high and comprise individual elements that are printed horizontally, then turned on their sides, interconnected and stacked. The prototypes explore how large-scale slurry-based 3D printers can also work with biopolymer materials at an architectural scale.

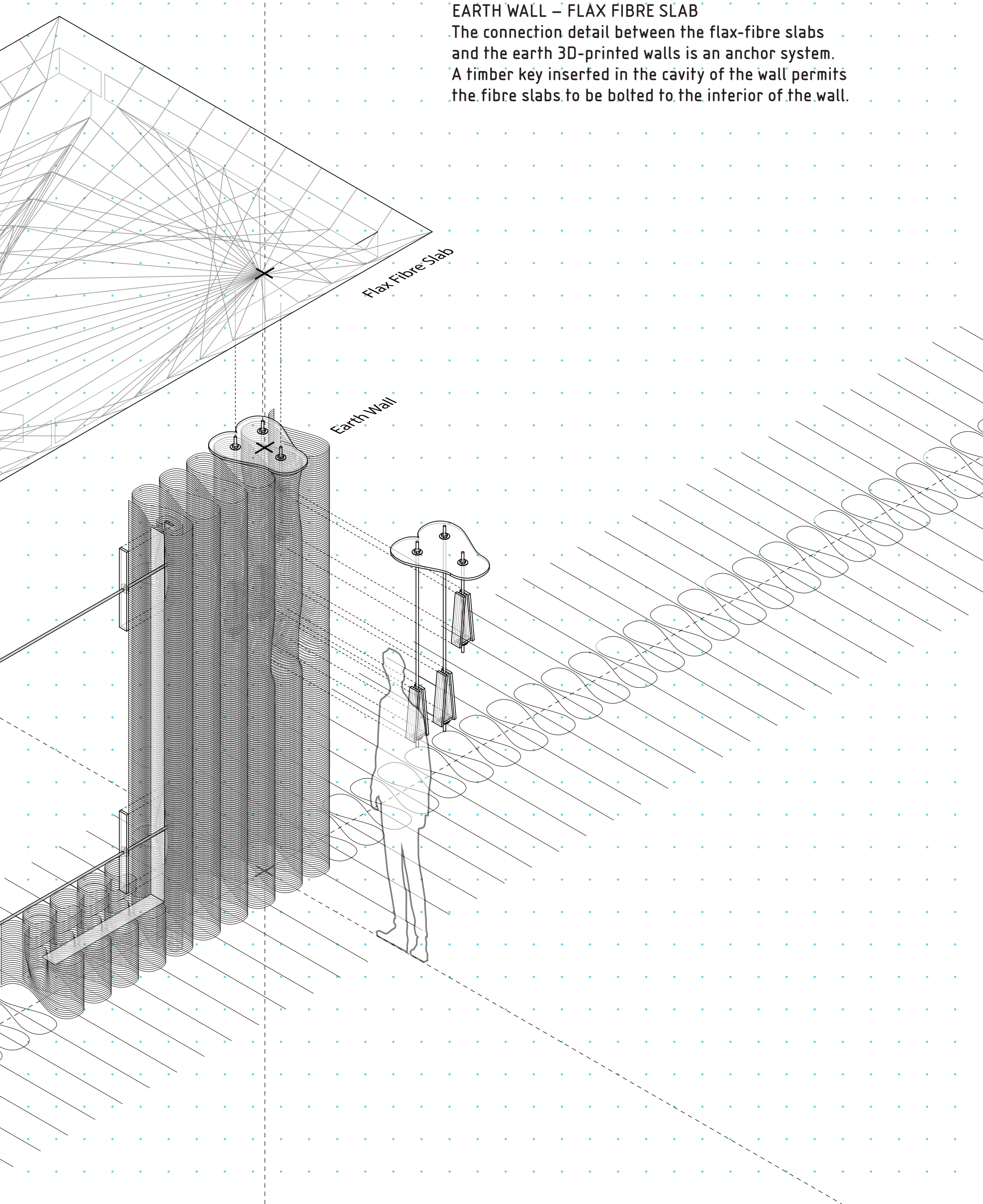
Merging as a Building System



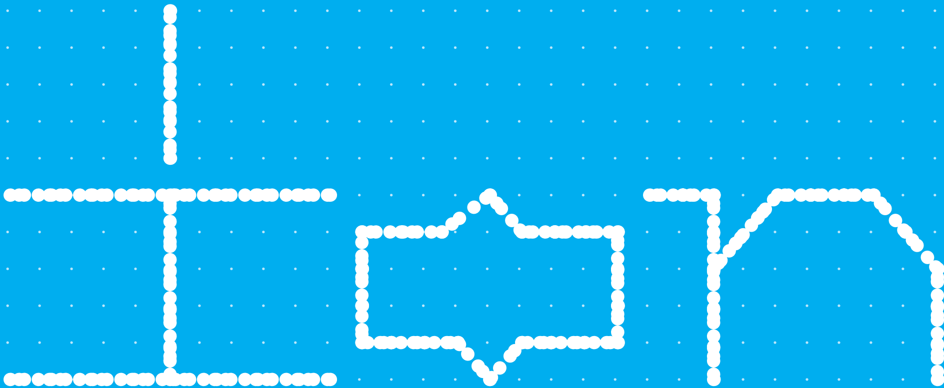
EARTH WALL – CELLULOSE SCREEN
This joint connects two 3D-printed biomaterial components, with a tolerance of up to 50 mm. An offset in the cellulose screen provides a means to place it precisely in a printed slot in the earth wall. This architectural detail has the potential for further refinement, as both materials can be post-processed using CNC-milling or manual chiselling.



EARTH WALL – FLAX FIBRE SLAB
The connection detail between the flax-fibre slabs and the earth 3D-printed walls is an anchor system. A timber key inserted in the cavity of the wall permits the fibre slabs to be bolted to the interior of the wall.

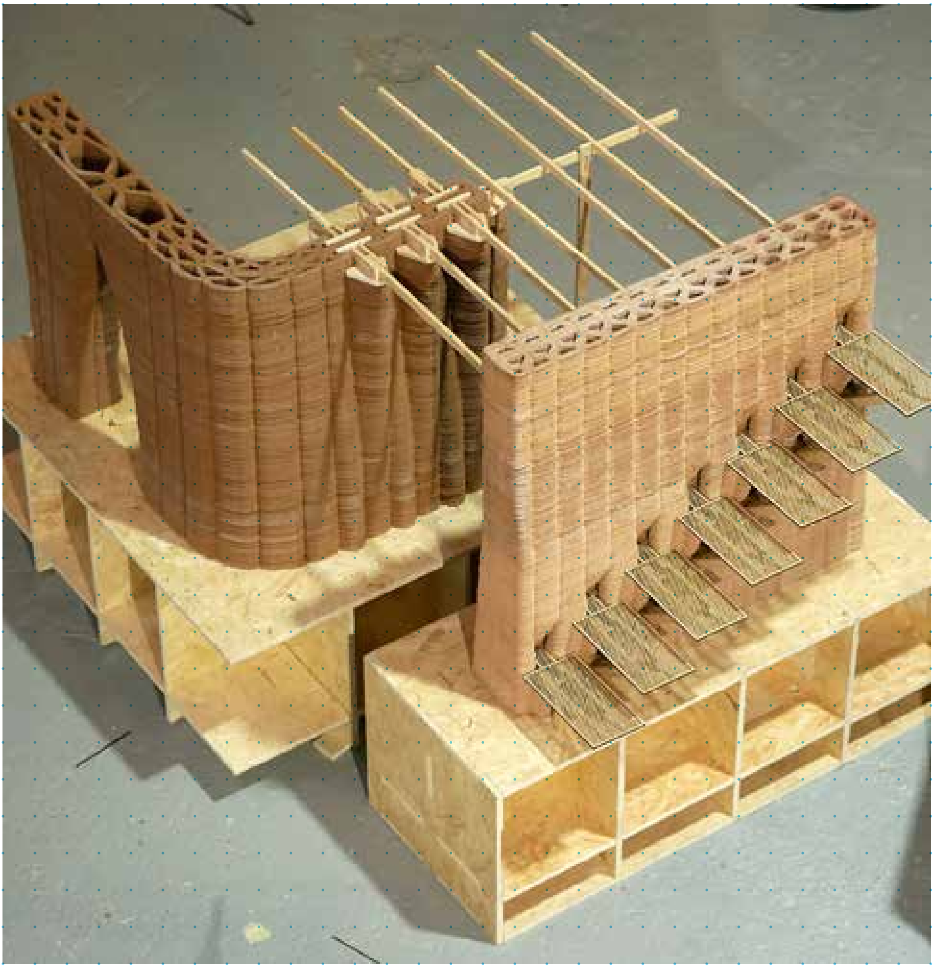


V15



A committed uptake of biomaterials in the building industry can transform how architecture is designed and built; by guiding the ideals of architectural design towards more resource-conscious and holistically sustainable building practices, and by overhauling long ingrained models and attitudes around collaboration and innovation across the industry.

Research Explorations



Scale-model of novel construction system using 3D-printed earth and timber (IAAC 3DPA with WASP)

3D-Printed Earth

For the past seven years, IAAC has researched 3D printing with earth at an architectural scale. Earlier prototypes using the robotic means available to the team, were designed and made by printing modules to be assembled on site. As the technology improved and progressed with cable robots and in particular the WASP crane made available through the *Living Prototypes* project, prototypes can now be printed in situ. This allows for the continuous printing of architecture using earth from the site, thus achieving a zero-kilometre transportation footprint.

Although only nine square metres, ongoing monitoring and testing has demonstrated that the prototype built at the IAAC Valldaura Labs in the first phase of the *Living Prototypes* project contains all the technology and details to be considered a complete building. It is weatherproof and structurally sound. Future research at IAAC can now tackle the fabrication of much larger buildings.

Full-scale prototype of novel construction system using 3D-printed earth and timber (IAAC 3DPA with WASP)

Flax Fibre-Winding

Core research at ITKE includes the investigation of fibre-composite materials, their architectural application and the study of innovative structural morphologies. In recent years, the main focus has shifted to the use of natural fibres and the exploration of bio-based matrices. Together with FibR, the ITKE team has been able to realise projects that explore new materiality from the perspective of both design and robotic fabrication.

One of the main challenges of using natural fibres is a reduced structural capacity; requiring increased material usage and extended fabrication hours to compensate. This project addresses the challenge by introducing timber into the material system, thereby maximising fibres under tension through a careful reallocation of timber and fibres in the structural system. With the small-scale prototype (two metres by one metre) on view as a table in the exhibition, the project undertakes a deeper exploration of interface geometries.

Scale model used to develop the fibre matrix of the ITKE-FibR Living Prototype

Test of the node detail carrying a lightweight building element made of timber and wound natural fibre

Bioplastic Prints

CITA investigates how concepts, methods and tools for design and manufacture need to adapt for when, in the future, architecture will be predominantly made from a heterogeneous set of biological materials. Their varying material qualities fit well to adaptive additive-manufacturing. New opportunities for design and building emerge. The biopolymers used in research at CITA and COBOD are prepared shortly before, or even during, the 3D printing process. The automation and integration of this process into a 3D printing system and the development of specific material recipes allow to mix and adjust the printed material continuously to local requirements. Elements with graded properties can be printed, and can for example be partly flexible due to local variations in the material strength or elasticity.

Grading by fibre content of printed cellulose in CITA workshop at University of Pennsylvania

Experiment with bone glue printing using different colours at CITA

Another Logic in Architectural Design

Project Team

Biomaterials can bring about a change in how we design and build. To embrace this opportunity, it is important that we recognise the unquestioned professional baggage of architecture, in order to identify how we as architects can finally build sustainably into the future.

In a biomaterial design-era, a building will be thought of as a process instead of as an artefact. We call this a 'thick' process, which will mean, for example:

— Always being engaged with the building and with others, both as an architect and as an inhabitant.

— Reconstructing the digital design chain around moments of remaking and participation in remaking.

— Using material behaviour and other complex factors to make design decisions, and allowing a change in the expression of architecture from the slender and clean modernist ideal towards the more chunky, tarnished and textured.

Expanding sustainable building practices with the social dimension

Sustainability remains the context and the challenge. With biomaterials architecture can simultaneously address the social and environmental challenges of sustainability. Building with biomaterials means building with materials whose primary condition is one of degradation, of becoming the biomass that they were. This requires much more deliberate cycles of reconstruction throughout the lifespan of a building, and therefore a more deliberate engagement with the people who are inhabiting or constructing it.

Truly circular biomaterials, such as earth or cellulose-based biopolymers, can be reshaped and reused with relatively little effort. Notwithstanding the challenges in terms of durability, inclusion in production processes at an industrial scale, as well as computational integration into the full technology of the digital chain, biomaterials nonetheless open opportunities for inhabitants to directly engage with building materials as they shape their living environments.

Speculative design for a construction system combining earth with a timber structure (IAAC 3DPA)

By explicitly necessitating a relationship between user and material, biomaterials can activate user participation in building processes. Not only for the maintenance of each private realm, but also to engage with the provision of community needs in buildings, neighbourhoods or cities – which includes, in many parts of the world, basic services and essential living standards.

As new building practices emerge with biomaterials, both bottom-up and professional construction can share similar digital fabrication frameworks. By making low-threshold digital building practices with biomaterials easily accessible worldwide, these sustainable materials can gradually replace conventional fossil-based materials.

Designing with material scenarios and life cycles

The urgent need to reduce carbon emissions, resource depletion and global warming leaves essentially no scope to absorb the planetary costs of any more building. Digitally fabricated construction with biomaterials allows individualised scenarios around the sources and life cycles of biomaterials to define architecture, on a project-by-project basis. Not only does this minimise environmental impacts, it also introduces interesting flexibility into architecture.

Speculative design for an earth-printed façade in Berlin (IAAC 3DPA)

Designing architecture in this way – basically in terms of its environmental life cycle assessment – means factoring in a material's energy costs across the entire lifespan of the building: from harvesting (with biomaterials) or excavation (with conventional depletable materials), through development, fabrication, disassembly and possibly decomposition, to refabrication for reuse. In this calculation, abundantly available biomaterials will fare significantly better than the fossil-based materials we use today.

With biomaterials, materials sources and life cycles can be thought together with the timescales of building components. Structural components have longer or more permanent life cycles than components in a building interior where functional uses and individual users can change often over its lifetime. The life cycles of biomaterial components can be designed to be longer or shorter. The biomaterial can be returned to its raw state and reworked into a new building component, or buildings can be disassembled and the biomaterial components reused. This challenges architectural design to think in terms of flexibility without over-standardisation.

Going beyond the primacy of optimisation in digital design

To date, the main emphasis in the digital design field has been on the efficient use of construction materials. With biomaterials this logic is dispersing. Biomaterials move digital fabrication away from minimisation towards other kinds of architectural ideals and logics.

In order for buildings to be effective stores of carbon, sometimes more rather than less material needs to be used. For example, the use of timber should be maximised. Good acoustic or energy performance actually requires more voluminous building components. The structural disadvantages of biomaterials, like flax or cellulose made from end-of-life paper, can be overcome by simply increasing the amount of these lightweight and plentiful materials.

With digital fabrication bespoke geometries become affordable. Each building element is individually designed and manufactured, and can therefore be made to fulfil multiple performance functions. For example, as the cellulose screens show, the porosity of the biomaterial can be tailored to allow humidity to penetrate or leave the material. Or, as the earth walls demonstrate, the voids in 3D-printed elements can be designed to include structural joints to other material components, ducts for ventilation and even technical appliances. The flax fibre slabs and bone glue wall panels demonstrate how, with an additive manufacturing process, the structural strength and visual appearance of a single material can be modified. This allows architecture to leave behind the logic of homogenous

Speculative design for a courtyard building in China using printed-earth with timber (IAAC 3DPA)

Speculative design for a building in cold climate printed in earth (IAAC 3DPA)

Speculative design for a building combining earth printing with a natural fibre-wound structure (ITKE and IAAC 3DPA) materials to engage instead with material grading that can react to specific performance needs.

With machine learning tools, the behaviour of biomaterials over time can be monitored and analysed. While working with biomaterials will necessitate a deep material understanding on the part of the designer, that is made all the more difficult by the heterogeneity and complex behaviour of the materials, designing with them encourages design thinking that is based on craftmanship-like intuition rather than total control. Computational techniques present architects with a different way of engaging with design and fabrication, that is about constant engagement and possibly repeated architectural interventions, extending into the post-design process.

Gradient-print made of cellulose and varying natural fibres, produced in CITA workshop at University of Pennsylvania

Rethinking standardisation in the building industry

To work with biomaterials means to work with prototypes, because full-scale prototypes are needed to gain a reliable understanding about material behaviour. This entails moving away from standardisation, bringing potential for creativity and innovation across the building industry.

The nature of biomaterials negates ISO standards, material classes and grades. Both the concept of standards and their rigidity need to be rethought to facilitate designing through the behavioural control of materials. A change from very long-term analytic-explanatory models to quicker and circular predictive-accuracy models, will support architecture that has inbuilt flexibility to change over time.

A switch to a more experimental, prototype-based approach in architectural design means working with predictability and margins of error instead of certainty and requiring continuous data collection and interpretation. This shapes a building practice engaged with constant monitoring and reconstruction rather than ensuing endurance. Nor does this challenge prevailing engineering concepts in current building practice, where little information aside from energy consumption is collected once buildings are in service, embracing observation and stochastic practices also poses challenges for architectural design. Which aspects need to be closely controlled and which don't? What benefits, drawbacks and implications are connected to the various digital tooling options?

Making any innovation part of mainstream practice only happens when the innovation has been implemented so frequently that it has proven itself. Bringing biomaterials into mainstream building practice needs space for initial experimentation. While construction companies, housing providers and property developers might have strategies on sustainability, they tend not to be open to the risks of experimentation towards innovation. This leaves the cost and risk of innovation with the smaller players in the industry, 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 left.

It is time to identify what needs to change. Which inherited ways, instruments and values have become our unquestioned baggage, and which can actually envision and bring about a more responsible way of building on this planet into the future. Biomaterials present a significant and exciting chance in this regard.

Project

Team

3D-Printed Earth

IAAC – Institute for Advanced Architecture of Catalonia, Barcelona

The Institute for Advanced Architecture of Catalonia (IAAC) is a centre for research, education, production and outreach, with the mission of envisioning the future habitat of our society and building it in the present. IAAC follows the digital revolution at all scales to expand the boundaries of architecture and design to meet the challenges faced by humanity. IAAC is an experimental and experiential centre, where one learns by doing, through a test methodology that promotes real solutions.

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Alexandre Dubor *3DPA Director*
Oriol Carrasco *3DPA Senior Faculty*
Yara Tayoun *3DPA Coordinator*
Ashkan Foroughi *3DPA Computational Expert*
Secil Afsar *3DPA Fabrication Assistant*
and all the students and faculty from the 3DPA program 2022/23

WASP, Massa Lombarda

3D printing is at the heart of WASP; from a small and fast printer that materialises objects made of bioplastics, clay and biocompatible materials to large printers capable of manufacturing walls. The aim of WASP is to build 'zero-mile' homes, using materials found in the surrounding area. A project like this requires the printing machine to be portable, adaptable to different contexts, and have a low energy consumption.

Francesca Morretti *Head of Communication*
Lapo Naldoni *Engineer and Project Manager*
Massimo Visona *Architect and Mechanical engineer*
Massimo Moretti *Founder*

Flax Fibre-Winding

ITKE – Institute of Building Structures and Structural Design, Stuttgart

The Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart focuses on the integration of structural design and architecture. The research interests engage in material science for the production of high-performance structures, lately especially in the use of natural fibres and the exploration of sustainable material systems, integrating computational engineering and advanced analysis methods into full-scale prototype development.

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Ioannis Moutevelis *Student Assistant*
Jan Knippers *Professor and Institute Director*

FibR GmbH, Kernen

FibR is a construction company realising architectural fibre-composite structures for load-bearing structures, facades, and interiors. FibR's computational design and robotic fabrication methods explore novel designs and create resource-efficient products. The interdisciplinary team offers vertically integrated digital construction services across all project phases ranging from concept development design assistance and building component certification to robotic production and on-site installation.

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Christo van der Hoven *Digital Design and Fabrication Expert*
Julian Fial *Head of Development and Fabrication*
Moritz Dörstelmann *Professor, Founder and CEO*

Bioplastic Prints

CITA – Centre for Information Technology and Architecture, Copenhagen

CITA is an innovative research environment exploring the intersections between architecture and digital technologies. Identifying core research questions into how space and technology can be probed, CITA investigates how the current forming of a digital culture impacts on architectural thinking and practice. CITA works in a biomaterial paradigm. It investigates computational processes for design, fabrication and use of buildings for a future fully circular and sustainable building practice.

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Carl Eppinger *Research Assistant*
Konrad Sonne *Research Assistant*
Tim Marvin Bruder *Research Assistant*
Adrian Rygh Bruun *Student Helper*
Arianna Rech *PhD candidate DTU*
Anders Egede Daugaard *Associate Professor DTU*
John Harding *Lecturer UOR*

COBOD International A/S, Copenhagen

COBOD is the global leader in 3D Construction Printing (3DCP) solutions. By partnering with customers, academic institutions and suppliers around the world, COBOD aims to disrupt the global construction industry. Many firsts in 3DCP have been executed using COBOD's technology, including the first two- and three-storey buildings in Belgium and Germany, the first villa in Dubai, first buildings in Africa and the first windmill turbine bases.

Alma Bangsgaard Svendsen *Architect and Project Manager*
Ole Ellinghausen *Head of Manufacturing*

Coordination and Curation

BBSR – The Federal Institute for Research on Building, Urban Affairs and Spatial Development, Bonn

The innovation programme *Zukunft Bau* of the Federal Ministry for Housing, Urban Development and Building (BMWSB) provides important impulses for the building industry. The Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) at the Federal Office for Building and Regional Planning (BBR) is the project management agency for *Zukunft Bau*. The BBSR is a research institution in the portfolio of the BMWSB. It advises the Federal Government on tasks related to housing, real estate and construction as well as urban and spatial development.

Helga Kühnhenrich *Head of Division, Research in Building and Construction*
Arnd Rose *Research Fellow at Division for Research in Building and Construction*

ANCB The Aedes Metropolitan Laboratory, Berlin

ANCB is a unique interdisciplinary platform for urban discourse at an international level, exploring the interplay between the built environment and social life for the future of our shared habitat. Through its programme, ANCB contributes substantially to the discourse of space making in its changing political, societal and cultural frameworks. The outcomes and ideas thus generated have been captured in a series of publications and are documented in an open-access video archive.

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