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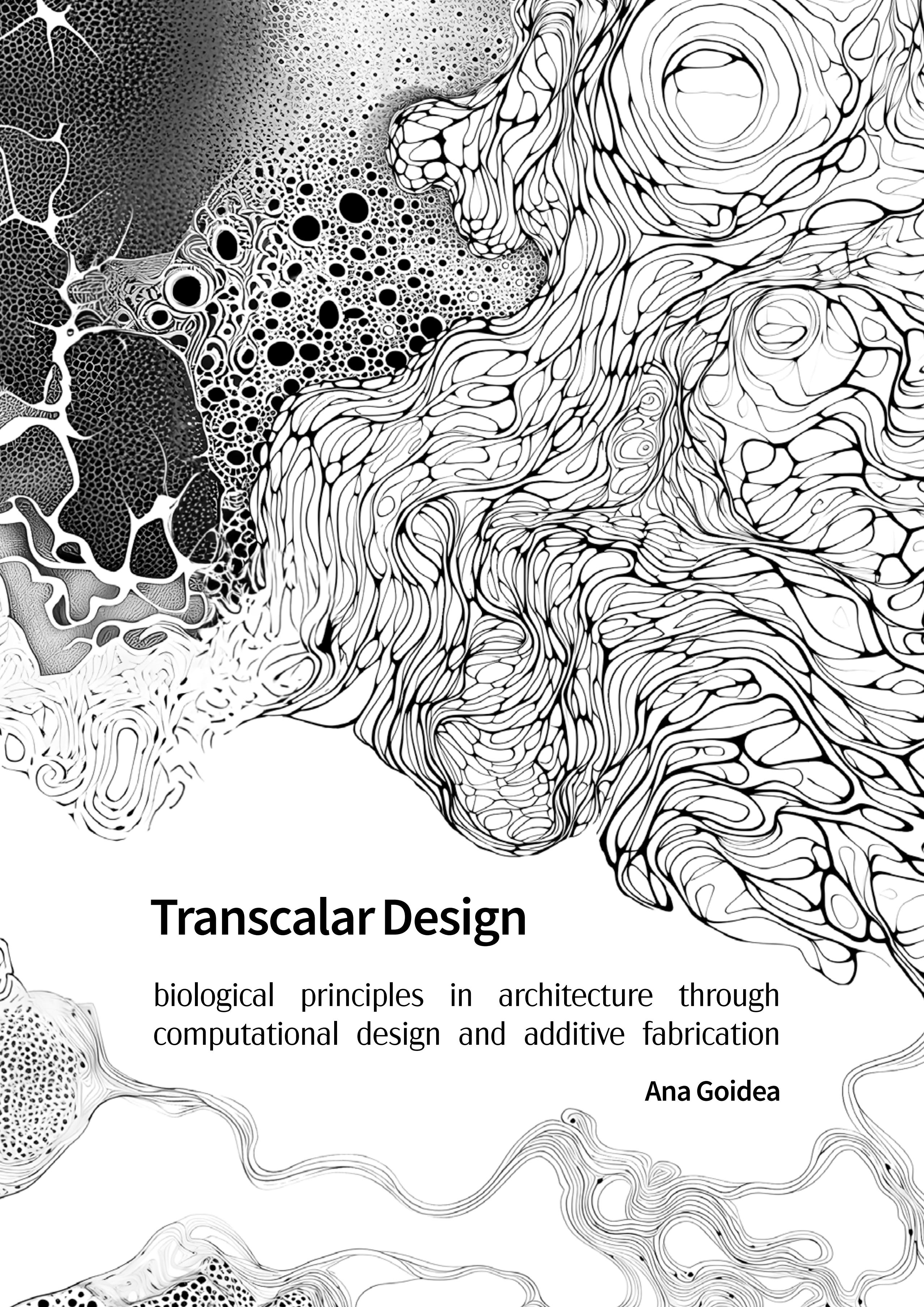

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DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 2nd of November 2023 at 09:15 in The Birgit Rausing Hall at Skissernas Museum.

Faculty opponent

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Abstract:

Architecture is currently facing a period of transformational change which is driven by an increasing awareness of sustainability imperatives combined with technological advancements in the form of digitalisation of design and fabrication processes. These issues both introduce new layers of complexity and necessitate strategies to navigate them. This thesis explores an aspect of this transformation found in the evolving intersection of computational design, digital fabrication, and biodesign, suggesting that computational design methods represent an opportunity to learn from and deploy principles of biology in order to address this challenge of complexity.

The dissertation defines and develops the concept of transcalarity as an organizational principle that describes complex systems by emphasizing and acknowledging interdependent behaviors across multiple scales. This takes place within a research-by-design framework, which links the varied disciplinary methodologies employed in the research experiments and leverages computational capacity to manage the complexity of working with living matter in design and fabrication.

Throughout this work, three research experiments address the challenge of integrating biological principles in architecture through different design approaches: Pulp Faction employs biofabrication under a computational framework, resulting in a 3d printed architectural column grown from fungal biocomposites. Meristem Wall investigates the interdependencies of functional integration and self-organization through complex geometry, resulting in a full-scale wall section connecting interior and exterior environments. Lastly, Swarm Materialization investigates in a theoretical arena the design process responsive to relationships between self-organization, digital fabrication, and material behavior through additive manufacturing of clay depositions guided by an algorithm that simulates several cooperating construction agents.

The three experiments contribute with design and fabrication methodologies, and two of them have been presented in the form of demonstrators. These methodologies include protocols for fungal biofabrication and bioFDM printing methods, ranging from species selection and microbiological workflows to substrate composition and design methods, on to computational design strategies that potentially enable the design and production of large volume, high resolution building elements with functional integration and gradation.

This thesis presents an investigation and elaboration of scalar interdependencies in digital design and fabrication methods and argues that these transcalar aspects are key to successful strategies for addressing sustainability challenges in architecture through the integration of natural systems and materials in the built environment.

Key words: architecture, additive manufacturing, generative design, biodesign, fungal composites, metamaterials, biofabrication

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Table of contents

Popular science summary

The built environment represents a large portion of the ecological footprint of human activity; it is responsible for the largest proportion of carbon emission, consumes vast amounts of resources, and contributes to significant waste. To address this and find new ways to construct buildings in sustainable ways, the field of architecture needs to look towards new technologies and new inspiration.

This thesis explores how nature can serve as a model for such endeavors. Using new and emerging technologies such as 3d printing and design generated through algorithms, possibilities open up for buildings that are full of complex form, intricate detailing, and added performances. Here, material and form interact to drive the building's functional performance.

Such structures, while new to architecture, are already present in nature, as biological organisms rely on similar principles. The projects explored in this thesis take inspiration from living organisms: from the transformative power of fungi to repurpose waste at a molecular level and create new material systems and structures, to the remarkable ability of termites to arrange earth into towering structures that harness the power of wind and sun to create a suitable habitat.

Three projects are the base of these studies: *Pulp Faction* presents an architectural column made from sawdust and living fungus, 3d

printed into a functional shape and fused together by the growth of the fungus in the wooden substrate. *Meristem Wall* is a full-scale building envelope section 3d printed in sand, designed to mediate between human habitats and the ecosystems that surround us. Its complex shapes and their performances could not have been made without 3d printing or without using programming to generate and manage its geometry. The final project, *Swarm Materialization*, delves into the type of processes that termites use to construct their elaborate mounds, using real time feedback through 3d scanning, 3d printing of clay, and agent simulations.

Together, these design experiments highlight a fundamental principle of biological design: natural structures are interconnected across scales, and entirely interdependent. The core idea of this doctoral dissertation is the *transcalar design* framework. It presents an alternative to industrialized simplifications, by drawing insights from how natural systems work. In essence, biology remains the most advanced manufacturing technology we know.

Publication list

Papers

1. Goidea, A., Floudas, D. & Andréen, D. (2020). Pulp Faction: 3D Printed Material Assemblies Through Microbial Biotransformation. *Fabricate 2020: Making Resilient Architecture*. Edited by Burry, J., Sabin, J., Sheil, B., & Skavara, M. UCL Press, London, pp. 42-49.

2. Goidea, A., Floudas, D. and Andréen, D. (2022). Transcalar Design: An Approach to Biodesign in the Built Environment. *Infrastructures*, 7(4):50.

3. Andréen, D. & Goidea, A. (2022). Principles of biological design as a model for biodesign and biofabrication in architecture. *Architecture. Structures. Construction*, 2, pp 481–491.

4. Goidea, A., Popescu, M. & Andréen, D. (2021). Meristem Wall an exploration of 3d printed architecture. *ACADIA 2021: Realignments: Toward Critical Computation*. Edited by Bogosian, B., Dörfler, K., Farahi, B., Garcia del Castillo y López, J., Grant, J., Noel, V., Parascho, S., & Scott, J. pp. 438-443.

5. Goidea, A., Popescu, M., Johansson, A., & Andréen D. Algorithmic modeling of functionally graded metamaterials in 3d printed building envelopes. *3D Printing and Additive Manufacturing*. Submitted, review under progress.

6. Andréen, D., Goidea, A., Johansson, A. & Hildorsson, E. (2019). Swarm Materialization Through Discrete, Nonsequential Additive Fabrication. *IEEE 4th International Workshops on Foundations and Applications of Self* Systems (FAS*W)*, Umea, Sweden, pp. 225-230.

Exhibitions

7. bioDigital Futures. Andréen, D. & Goidea, A. (2021). Venice, Italy. May-October 2021. Pedrana, Lucia De Stefano, Rachele and Valeria Romagnini, eds. *Time Space Existence, European Cultural Centre*. Published following the exhibition Time Space Existence at Palazzo Mora, Palazzo Bembo and Giardini Marinaressa, Venice, Italy.

8. Xenoikos, hidden worlds. Goidea, A. Spark gallery, Malmö, Sweden. October 2020.

Prologue

It took a fall through the rabbit hole for Alice to see that some things were inaccessible to her. The tiny door, with the tiny key, that she just couldn't fit through. The huge table, that she couldn't reach. So she had to keep going: follow the strange thread, drink the potion, eat the uncanny cookie. Only by becoming minuscule, and then gigantic, she could discover the strange world behind the door, hiding in her garden. This change of scale is what allows her the perspective through which she now understands and interacts with the new world. Along with Horton (2021), I too believe that we have already entered Wonderland. We are now aware of these scales; and even though we are not always forced to engage with them outside our immediate sphere, we also cannot go back. We cannot climb up the rabbit hole we slid through.

This work aims to explore some of what is there for us, as designers and architects, as creators of things that have a geological impact on our world, in the scalar world beyond. What can we learn from it, about it, and about us? How can we interact with it, and why should we?

So, follow me, if you will, let's drink the potion together. The only way out is through.

For those who call distant regions of the scalar spectrum home.

- Zachary Horton, The Cosmic Zoom

1. Introduction

This thesis is an exploration of transcalarity as a key element in complex material systems. It is positioned at the intersection of the fields of computational design, digital fabrication, and biodesign. It examines their implementation in architectural design through three different design experiments.

It is a compilation thesis composed of six publications that describe the research findings of three design experiments. These publications are appended in the last chapter. They are bound together by an umbrella text, the “kappa”, that provides context and discusses the wider implications and contributions of the research. The first two projects are finalized with research findings shown in the publications and in the kappa, whereas the third one is ongoing. This project is therefore described primarily in the kappa, and the associated published article is an overall outline of its principles and ambition.

Chapter 1 describes the social and material context to which the thesis responds. This concerns mainly the relationship between human societies and the surrounding environment, and the consequences of this relationship. It is framed with an emphasis on sustainability, and even though the thesis does not delve into quantified evaluations of the environmental impact of the work, it proposes alternative methods of operation which can hopefully have a positive impact in the world. Here are also outlined the research questions as well as the main hypothesis of transcalarity as a model for understanding systems and approach to architectural design.

Chapter 2 describes the research context in which this thesis sits and its relation to the field of computational biodesign, which is an aggregate of several disciplines including biotechnology and computational design. This chapter furthermore provides and clarifies relevant terminology.

Chapter 3 delves into the concept of transcalarity which serves as a cornerstone for this thesis. This chapter presents a brief elaboration on the concept of scale, followed by a reflection on the role of transcalarity in biological systems and its importance in successful implementation of computational biodesign. Furthermore, it outlines key concepts on how transcalarity can be integrated into architectural design processes, discussing potential benefits and challenges.

Chapter 4 outlines the overall methodology employed in the three research projects of this thesis as well as the distinctions between the processes. The overarching methodology - research by design - is considered in terms of its relation to biodesign, computation, and transcalarity.

In-depth descriptions of the three design experiments as they took place within three research projects are provided in the next chapters. These are chapter 5, *Pulp Faction*, chapter 6, *Meristem Wall* and chapter 7, *Swarm Materialization*. These each include an introduction to the project's connection to biological systems, its respective research context and background, and a detailed methodology section. Every project includes a visual journal subchapter which complements the narrative through photos of tests, experiments, and the development process. The project descriptions conclude with reflections on the implementation of transcalarity within the respective project.

Chapter 8 provides a discussion on the results and findings of the thesis which includes reflections on sustainability and how it is impacted by a transcalar framework. It also explores, in more general terms, the domain of computational biodesign and transcalarity as understood through this work, speculating about possible future directions.

Lastly, the final section presents the publications associated with the thesis projects. In addition to conference and journal papers, two of the projects have been published in exhibitions which are also included and documented in this section.

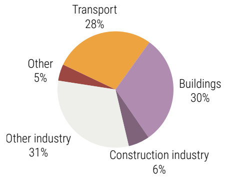
1.1. Context and background

The term Anthropocene was proposed by Paul Crutzen (2000) to define a new geological epoch, representing the magnitude, variety, and long-term impact on the land and composition of the atmosphere that human activity has caused. It is estimated that these impacts will be observable in the geological strata for millions of years into the future (Lewis & Maslin, 2015).

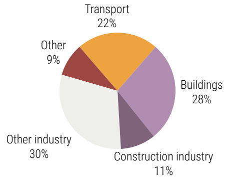
The construction industry is a major contributor to resource consumption, as well as CO_2 emissions and pollution. According to a report from 2019 published by the United Nations Environment Programme, the building and construction sector has the largest share of all sectors, accounting for 36% of global energy use and 39% of CO_2 emissions (Fig. 1) (Global Alliance, 2019). The latter have dropped to 37% in the report from 2021, although this is largely an effect of construction activities decreasing worldwide due to the impact of COVID-19 (UNEP, 2021).

The human population is growing, and urbanization is constantly increasing, with estimates that 68% of the population will live in cities by 2050 (Ritche & Roser, 2018). This means more needs to be built: the total building floor area is expected to double by 2060 (UN Environment, 2017). Urban sprawl and agricultural extension will take even more land from the surrounding environment, which threatens to further deplete biodiversity. Beyond the rippling ecological loss, this also impacts the human psyche. Several sources show a positive link between exposure to the natural environment and human mental health (Cox et al., 2018), (Dobson et al., 2021), (Berman et al., 2012), (Southon et al., 2018). This highlights the risks involved in reducing the natural environment further through unsustainable urbanization and raises the question of how we can keep the necessary urban growth while maintaining natural environments inside cities.

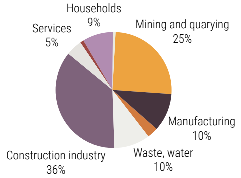
The reliance on non-renewable and finite resources in the construction industry, whose sourcing to a great degree depends on mining and extraction, is problematic. Furthermore, many of these are



Energy Consumption



CO_2 Emissions



Waste Generation

Fig. 1. Contributions to energy consumption, emissions and waste by sector.

not used raw, thus necessitating energy-intensive processes to turn them into the most used construction materials, such as concrete and steel (Dahy, 2019). Moreover, some of these processes by themselves generate CO_2, like in the case of cement production: 11% of the CO_2 emissions of the building sector resulted from the manufacturing of building materials such as cement, steel, and glass (Global Alliance, 2019).

And at the end of the life-cycle perspective, construction contributes to 35.9% of EU waste generation (Eurostat, 2018). Except for a few EU countries, only about 50% of construction and demolition waste is currently being recycled (European Commission, 2018).

But another implication of this accelerated growth of cities is a reason for and an opportunity to shift the modes of operation – and perhaps more radically – to heal and repair some of the damage that has been done. Every crisis is also an opportunity for change. As Hensel argues (2012), the natural environment is an integral part of the design problem, and ecological perspectives and knowledge are critical in the field of architecture. This relates to the sourcing and processing of materials employed, as well as to how the built environment impacts ecosystems during construction and in operation.

Despite its significance in society, architecture has adopted digitalization to a far lesser extent than other industries, ahead only of agriculture (Sezer et al., 2021). Additionally, the main efforts to digitalize the architectural industry have predominantly revolved around the use of Building Information Modelling (BIM). These tools and the limited implementation of automation in the production of prefabricated parts have primarily been aimed at enhancing the speed and efficiency of current building techniques - “computerization” of tasks rather than employing computation to generate added design value (Knippers et al., 2021).

However, the possibilities that digital and computational processes bring to the architecture and construction industry extend far beyond production speed, efficiency, and digitalization of already established processes, or in other words incremental change within the same building culture. The incorporation of these digital tools and methodologies can offer a compelling opportunity to reimagine and transform the ways we approach architectural production, assembly, and utilization towards a more integrated practice.

Considering the urgent need for a different material culture, alternative design and production methodologies based on emerging technologies following biological models could provide a way forward. The argument in this thesis is that models inherent to biology can contribute to improving the sustainability of the built environment. These models are linked to resource use, circularity, matter and information exchange, performative geometries, adaptation, interdependence, homeostasis, distributed logics, self-organization, and diversity. However, architectural thinking through such new and diverse material systems requires fundamentally different methods of design and fabrication (Ramsgaard Thomsen, 2022), which need to be developed synchronously.

To address this issue and tackle some of its socio-environmental challenges, the European Commission has suggested employing nature-based solutions: “inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions” (2017). This rings true and is a fundamental ambition of this work, but how this can be implemented is an open question that requires a much more specific context and an explicit approach to gain meaning.

1.2. Research questions

This thesis starts from the premise that integrating nature-based solutions into architecture can foster sustainability. However, how can this integration be done? What are methods to conceptualize and apply it? It has been more than half a century since Frei Otto concluded that “The altered environmental conditions of today can no longer be mastered with the architectural resources of the past… The relationship between biology and building is now in need of clarification due to real and practical exigencies. The problem of environment has never before been such a threat to existence. In effect, it is a biological problem.”

(Otto, 1971). But which are then the new architectural resources that can interface with the environment in the current context?

I hypothesize that while biodesign can be one such resource, its integration in architecture brings new and specific challenges that can be addressed through generative computation, digital fabrication, and the making of new material systems. Therefore, the broad research question addressed here is: *How can biological principles be integrated into architecture through computational design and additive manufacturing?*

The inherent complexity of natural systems is conflicting with the modes of operation orchestrated by industrialized modernist principles. By relying on simplification and reduction, they are bound to encounter complexity ceilings (Bentley, 2007). The paradigm of biodesign represents an alternative to the current focus on industrialized mass production and homogenization in the building industry. This thesis argues that a key element in the functional complexity found in natural systems is transcalarity. By this term I refer to the complex interweaving of different scales, in terms of materiality, form, function, and process. The modernist approach attempts to reduce interdependence in order to decrease complexity, thus neglecting to address transcalarity and with it one of the foundations of function and performance in biological systems. This can inadvertently lead to undesirable scalar effects, as opposed to the integrative outcomes seen in biological systems. If these transcalar interdependencies are desirable, even necessary in the design outcome, they cannot be eliminated from the design process. This insight necessitates a dual investigation of transcalarity - on the one hand how it *performs* in an outcome, and on the other how it can be incorporated into and resolved within the design process.

Digital tools for design are proposed as a bridge to realize and integrate complex natural processes into architecture, and this leads to the following research question: *How can transcalar effects be identified and used in design processes, material systems, and fabrication methods?* Engaging with this inquiry through digital and physical experiments opens up several architectonic possibilities and introduces an exploratory question related to both digital fabrication and environmental implications: *What kind of relevant relationships emerge in scalar translations involving natural systems integrated into architecture?*

The aim of this thesis is to explore the implications of these questions through methods of biodesign and biofabrication using generative design processes and digital fabrication. Material exploration took place in all three projects, which resulted in full-scale demonstrators in two of them.

1.3. Aims and goals

This thesis seeks to formulate a framework for observing complex phenomena occurring in the natural environment through a scalar perspective, and subsequently applying it to the production of architectural designs. This takes place through three design experiments, each integrating elements of biodesign, generative computation, and additive manufacturing in different ways. Given the complexity of integrating these topics in architecture and the multifaceted interactions within and between them, these design experiments serve as a rich terrain for reflections on transcalarity.

Positioned at the intersection of diverse disciplines including biology, applied biotechnology, computation, digital fabrication, and material development, this thesis incorporates methods from each while delving into various sub-topics. However, rather than reaching the depths of the individual disciplines, this work is more focused on exploring the intersections of these fields in an experimental and non-linear manner.

1.4. Scope of the research

This thesis explores a potential shift in architectural practice, where digital tools together with a deeper understanding of its relationship to the environment can enable a more integrated approach to design and construction. The study aims to formulate a framework, centered around the concept of transcalarity, that helps to understand and address the challenges that follow this potential new paradigm. This framework is based on and explored through three design experiments that together attempt to capture a largely unknown and complex potential. On their own neither of these experiments captures or addresses the entirety of the challenge at hand, but together they lay the foundation for a future process that is more complete.

Apart from articulating this theoretical framework, the design experiments were intended to result in applicable insights and protocols that can form the basis for further research. As such, they contain particular formulations, methods, and tools, whose use and application are evaluated in mostly qualitative terms. The research however does not aim to produce market-ready solutions. The demonstrators are therefore not evaluated with regards to ecological impact or cost efficiency. Similarly, the computational methods that are used and developed are described in principle along with their intended use, but it is not within the scope of the research to provide ready to use software solutions.

With the research methodology anchored in design disciplines, its main intention is to open avenues and test broad hypotheses that fall on the intersection of multiple disciplines, suggesting how disciplinary practice may need to adapt to respond to new challenges. It is understood that the particular outcomes need to be further developed both within and across the different disciplines involved.

Before this kappa delves into a more thorough description and discussion of these projects, the next chapter features an overview and explanation of important approaches and terms that are used in the thesis.

Life is not a protein soup.

\- Denis Noble

2. Integrative approaches in biodesign

This thesis covers areas that are on one hand parts of distinct fields – architectural design; computation, or computational design; additive manufacturing; and biology – and on the other hand, are rapidly evolving in their methods and terminology. This chapter will clarify the disciplinary context, the terminology used and suggest how the combination of these fields can offer significant synergies and benefits.

The first subchapter addresses biology and design, and delves into key terminologies of biodesign in architecture, an area which is increasingly gaining traction. Biodesign encapsulates an area that has evolved over the years to encompass a vast array of practices and methods, being developed within both academic research groups and emerging industry applications. As biodesign does not have a formalized movement, this results in the lack of an established terminology, with descriptions often used inconsistently in the current literature (Moroni et al., 2017). Defining the terms in this area as they are relevant in architecture is important in clarifying the positioning of the work in this thesis.

The second subchapter addresses the field of computational design, with regards to architectural tools and processes. Computational design has rapidly gained adoption and importance in academic and industrial practice. Several distinct approaches have been developed over time and these result in different kinds of outcomes that will briefly be discussed here.

The third subchapter concerns material computation, an area at the intersection of design and materiality that predated the use of computers, but which has come to greatly influence the use and understanding of computational design. Here I address the importance of bottom-up design processes, arguing for a design practice that is deeply rooted in an understanding of material performance. Material computation embraces a framework where design is informed by the material's innate properties and behaviors, rather than attempting to fully uniformize these. Its intersection with digital fabrication (in particular, additive manufacturing will be explored here), has opened new horizons for high specificity within material craft. The digital fabrication landscape is continually evolving, with the development of new material systems and processes.

The concluding subchapter will describe the territory where biodesign, computational design and fabrication, and material computation converge. At this intersection, a novel field emerges, which harnesses computational tools to navigate the intricacies of working with living matter in both design and fabrication.

Operating at the interplay between these domains, we can begin to reimagine the way we conceive of and engage with architectural design, particularly in the context of the current climatic crisis and technological landscape.

2.1. Biology and design

Biodesign is a wide term encompassing processes of designing with, as or for living matter (Goidea et al., 2022). Here, several defining terms exist, representing unique perspectives and methodologies within this field. This growing vocabulary reflects an evolution of thought and adaptation to contemporary needs over several decades, pointing to a multiplicity of approaches, each focusing on specific aspects and outcomes.

Since early times, humans have been fascinated by forms and efficiencies found in nature. This has influenced tools, dwellings, and other artifacts. One such early example is in the form of the Corinthian columns, dating back to the fifth century BC, where the acanthus leaf was integrated as a motif at the top of the columns (Britannica Online n.d.). This inspiration for geometries found in nature has continued throughout architectural history, leaving traces such as the movements of Baroque or Art Nouveau. This earliest wave can be interpreted as biomorphism, as its main intention is to apply organic shapes and patterns to architecture, giving a visual resemblance of natural elements. Moving closer to performative design, another term called biomimicry was later developed. It refers to the transfer of ideas from biology to design, focusing on function. It essentially aims at translating a function from a natural structure to a human-made structure, by replicating its original geometry. Although it was first coined by Otto Schmidt in the 1950s (Vincent, 2006), it can be observed earlier, such as in the flight machines designed by Leonardo da Vinci, which took inspiration from birds.

A pivoting point in this trajectory was made by D'Arcy Thompson, known for his seminal work "On Growth and Form" published in 1917. He investigated biominerals in organisms, and through a range of examples he provided a new explanation of how the morphogenesis of organisms can be explained through physical and chemical forces both internal and from the environment. He introduced an understanding of not just how forms give way to functions and therefore can be replicated to induce the desired functionalities, but also how forms in nature are products of forces and respond to these.

This is in line with the work later done by Turner where he uses the term biological design to refer to the morphogenetic process that connects genotypes to phenotypes[1]. By elaborating on how different processes and agents express DNA code in the form of spatial and functional organisms and structures, he defines biological design as the process that leads to "the remarkable coherence between form and function in biological structures" (Turner, 2008).

The early 20th century's Modern Synthesis in biology, which unified the ideas of heredity and evolution, provided a deeper grasp on how life operates at the molecular and genetic level. Together with technological developments, particularly in the late 19th and early 20th centuries, it has played a pivotal role in the emergence of biotechnology. Regarded at the same time a technological and a cultural phenomenon (Yoxen and Hyde, 1990), biotechnology involves the utilization

[1] Genotype is the code inscribed in the DNA, while phenotype is the resulting appearance and function of the organism.

of biological organisms, systems and processes in industrial and manufacturing settings (Bennett, 1998), through the direct interaction and control of living systems at a molecular and cellular level.

Interestingly, while biotechnology is a relatively recent term, its origins trace back to ancient times. Some claim that the use of recombinant DNA and genetic engineering are necessary for the correct use of the term. However, techniques like brewing and fermentation employed by Babylonians and ancient Egyptians can be seen as early biotechnological practices. Under this perspective, biotechnology is a long-standing discipline that has gradually advanced through technological and scientific developments (Bud, 1991). It illustrates a long history of human interaction, collaboration, and adaptation with microorganisms.

When it comes to the relevance of biotechnology for architecture, further emphasis will be on its application in the production of materials. The term biomaterials encompasses the widest range, as it refers to any material that has a biological association, so it is not very specific. Within this area, bio-based materials are defined as materials wholly or partially derived from materials of biological origin. These include wood materials and other biologically derived composites, such as straw, cotton, OSB, glu-lam, or bioplastics. They are not necessarily biodegradable, and they can be called biomaterials if they contain is at least 7% biomass (Lee et al., 2021).

Recently, biofabrication has been defined as a narrower field of material development within biomaterials. These are a new class of materials that use the living cells to create new composites from raw materials. They require the incorporation of living microorganisms as essential components into designed artifacts. This has marked a departure from traditional manufacturing methods and materials, moving the discourse beyond imitation and metaphor in the replication of a passive nature, to an active engagement and co-creation with its processes.

Biodesign will be further explored in this thesis through three projects, using the terms defined in this chapter. Through this work, I envision biodesign to be closely tied to the concept of transcalarity, implemented through computational design and digital fabrication, which will be expanded on below.

2.1.1. A note on ethics

Historically, biotechnology has been linked to industrialized animal farming, which poses both environmental and ethical challenges. The fears and hopes regarding this expansion touch upon complex issues. Could biotechnology reduce some of the current environmental challenges, and if so, are there ethical considerations into play when scaling it up for mass production? Is the moral landscape different when comparing microbial biotechnology's role in food and pharmaceutical industries to its use in construction? Additionally, how do these ethical concerns align with those arising in industrial forestry or other sectors using bio-based materials? At what point does the industrial use of living entities, be it grains, trees, fungi, or livestock, cross ethical boundaries, and how do we define those limits?

Navigating these complexities is critical, as Myers et al. point out: "The integration of life into design is not a magic bullet to solve these pressing issues. Nor it will be free from harmful missteps, deliberate missuses, or controversy. [...] These technologies will be wielded by people – the same biased and frail creatures who designed the world into a desperate mess in the first place. But the potential benefits, and the need to reform current practices toward an approach more in tune with biological systems, far outweigh the risks" (2012).

2.2. Computational design

Computers have been shaping architectural design for several decades. With the emergence of cybernetics in the 1940s and the development of the "Sketchpad" drafting tool in the 1960s (Sutherland, 1964), digital tools have increasingly permeated the production of architecture. Today, digital design - defined through the utilization of a computer at any stage of the design process - is nearly ubiquitous, ranging from rudimentary drafting tools like CAD software to complex machine learning applications.

One method of employing digital design is through parametric design, a term first defined by Moretti (1971) as the study of relationships between the dimensions of an architectural design based on parameters. Today, parametric design is commonly employed in Building Information Modeling (BIM) tools, where most design elements have sliding dimensions, allowing for variation throughout the design project. This implies a unified approach, with all elements and their parameters predefined at the outset of the design process, and a linear correlation between input and output.

The initial strategy of primarily employing digital tools for abstracted form-making, such as in spline drafting, which leveraged formal languages such as aerodynamics through curves and surfaces, still persisting today. However, this still did not bridge the gap between machines as drawing tools and machines as problem solvers (Carpo, 2023). While such digital tools speed up drafting processes and reduce costs, their purely quantitative applications are only partially relevant, as Mario Carpo (2023) asserts. It is more interesting, as well as more necessary to investigate their ability to open up novel opportunities, altering the ways we engage with information and matter in the design process.

In parallel with these developments, computational design (CD) emerged as a design approach driven by computational logic. Not restricted to the digital medium, it can also be realized through analog methods, as seen in the work of Frei Otto in his minimal surfaces and Antoni Gaudi’s hanging chain models. The advancements in computational tools and the array of CD methods available have enabled architects to expand the conceptual boundaries of the design process, fostering the exploration and evaluation of complex solutions, the development and application of advanced fabrication techniques, and the control of the design process at various stages (Caetano et al 2019).

More specifically bound to the digital realm, generative design has later emerged as a powerful design tool. Described as a method of creating complex patterns and forms from simple specifications (Caetano et al., 2019), this approach can produce solutions to complex problems less likely to be found through traditional problem-solving methods (Zee & Vrie, 2008). Known for resulting in outputs that are hard to predict from reading the algorithm alone, they are often employed in form-finding processes. In this context, the distinction between algorithmic and generative design as the degree of control between the output and the code as suggested by Caetano et al (2019) is less relevant; this level of control is on a continuum and depends on the type of algorithm and its implementation, rather than falling into binary categories. Consequently, in this thesis, these terms are used interchangeably.

The evolution of digital tools and methods in architecture has opened new possibilities for architectural design. The continuous advancements in computational design and generative algorithms have paved the way for a richer material practice through digital fabrication, while simultaneously enabling the interfacing with the complexity of environment and natural systems, exhibiting emergent properties that will be further discussed in the next chapters.

2.3. Material computation

The Western architectural tradition has long prioritized form over materiality, with abstraction frequently guiding design. This approach can be traced since the Renaissance era, elaborated by Leon Battista Alberti in his treatise “On the Art of Building”. Alberti advocated the idea that geometrical proportions, the lines, angles, and planes that define the building and its constituent parts are the most important aspect of the design process. He proposed that form should be conceived first in the mind and buildings should be derived from abstract geometric ideas, rather the pragmatic considerations of available building materials and their properties (Hendrix, 2011).

This distinction between the design process and its materialization remained fundamental in the production Western architecture for centuries, with few exceptions. Even Le Corbusier referred to architecture as the “pure creation of the mind” (Corbusier, 1946 in Hendrix, 2011). Despite the modernist call for “truth to materials” that emphasized tectonics, the approach still relied on an abstracted “essence” of the materials. This often led to a restricted set of structural and spatial typologies, typically adhering to a predetermined construction logic (Menges, 2015).

The industrial revolution of the last century brought simplification and a reduction of ornamentation to architecture. The efficiency and repetition of the Fordist industrial dream pervaded architectural practice, often resulting in structures that were fast, cheap, modular, and stripped to functionality (Oxman, 2010).

The later development of the digital revolution allowed for an expansion of possibilities of formal expression, releasing new aesthetics as illustrated by Greg Lynn's "blobitecture" and the computational experiments of Frank Gehry turned into building elements. Despite the formal liberation, this resulted in an even further separation from the material, locking in design elements before considering materiality or construction logics. Architecture began to exist independently from its materiality, with "form-making" becoming its own knowledge domain (Oxman, 2010).

However, perhaps due to the current material culture crisis, or the technological developments that are now not only able to generate complex systems, but help us understand and interface with them – or both – a new materiality is emerging in the design culture. In this perspective, material properties and behavior serve as active design generators. The continuum between the microscale of material constitution and the macroscale of architectural material systems is understood in terms of reciprocal behavior and performance capacities (Menges, 2012). Materiality is no longer a passive form recipient but an active agent influencing design generation and architectural performance (Menges, 2015).

Furthermore, material systems in architecture can now be seen as the synergetic outcomes of multiple influencing variables and balancing divergent design criteria, which invariably include interaction with the environment (Menges, 2014). Instead of relying on generalizations, the design process can now be derived from specific compositions of forces and materials, synthesizing material systems, structural systems, and their behavior along with the spaces they generate into one fluid process (Menges, 2014).

This paradigm aligns with the new materialist perspective of thinkers like Karen Barad, for whom matter is process and is defined by its actions and movements (Gamble et al., 2019). This shift repositions the relationship between design and materiality in a continuum, emphasizing a bottom-up design strategy that works generatively with the inherent properties of materials.

These approaches seem to point to a return of the vernacular understanding of the materiality, approached however through a new lens. Considering vernacular traditions where affordability and local availability of matter and knowledge (also seen as craft) are essential, the notion of a neo-vernacular might incorporate locality and data-rich practices as translation from craft.

Ecological issues emerging from the failures of modernity necessitate a renewed materiality, and an approach where design is being reintegrated with materiality. This perspective potentially carries profound ecological significance, as it challenges the root conditions of our current culture of waste by reconsidering materials' role in design generation and production (Oxman, 2010).

2.4. Materially driven computational biodesign

In 2012, Michael Hensel asked "[w]hat kind of disciplinary affiliation between architecture and biology is needed in order to tackle the complexity of the problems arising from the interaction between the human-made and the natural environment?" (Hensel, 2012).

Based on the arguments presented above, and within the contemporary landscape, I propose that an answer may be found in a synthesis of the above fields, a materially driven computational biodesign. By bridging biological insights, computational power, and material intelligence, new prospects are opened up for the development of nature-based architectural solutions. This is a fundamentally cross-disciplinary endeavor: the synthesis of these fields is a constellation of overlapping spheres of knowledge and making, each bringing unique perspectives and potential solutions to the current architectural context.

Moving beyond biomimetics, the work presented here learns from biological design, using natural processes to create an architecture that actively interfaces with its environment. Computational design guides these processes, continuing the development of "biotechnical architecture".

As noted by Ednie-Brown (2013), ten years ago biotechnical architecture was in a stage akin to that of digital architecture in the early 90s - tinkering with new materials, organisms, and processes, yet still speculative. However, with an increasing number of successful applications of biotechnology in architecture and design, the convergence of biodesign and computation could be a new frontier in architecture.

The use of computational tools is essential to the integration of transcalarity into design processes. The introduction of digital fabrication into architectural making calls for a more profound engagement with material systems (Ramsgaard Thomsen, 2022). The simple cause-and-effect relationships typical in parametricism are insufficient to map the behavior of and work with non-linear materials, indicating the need for non-linear tools. To navigate the complex interrelationships and concurrent requirements across different scales, there is a need to shift away from the linear dynamics of parametric design in favor of generative computational models.

The work presented here actualizes biodesign through generative models, digital fabrication, and material computation, as described by Menges (2012): “In architecture, computation provides a powerful agency for both informing the design process through specific material behavior and characteristics, and in turn informing the organization of matter and material across multiple scales based on feedback with the environment”.

Heterogeneity, both in materials and behavior across different scales, forms a critical aspect of this thesis. Industrialization’s approach towards it, mainly managed through classification (Ramsgaard Thomsen, 2022), leads to a culture of waste production that we can no longer afford. There is a compelling need for design and fabrication processes that can manage multiple levels of information simultaneously. If we define computation as the processing of information, then materials can compute (Menges, 2012), and thus we can employ this capacity of information processing to ripple through scales upwards. Such methods of individualizing material composition and steering growth present a promising path forward.

Reality provides us with facts so romantic that imagination itself could add nothing to them.

- Jules Verne

3. Transcalarity

The central position of this thesis is the concept of transcalarity. I use the term transcalarity as an organizational principle of complexity that observes interdependent behaviors at several scales of magnitude. In other words, complex systems are transcalar; the implications are that on one hand they operate at several scales simultaneously, and on the other that they are shaped and affected by several scales. This term, not confined to the physical size or magnitude, encapsulates the intricate and extensive networks existing across different domains, levels of organization, and scales of operation.

The connectivity and interdependence across multiple scales that transcalarity implies can be found in any range, narrow or broad, from the microcosm to the macrocosm. The term *transscalar* has been used in global studies to understand societal issues and their interdependence at territorial scales. Oftentimes it investigates such links at the scales of local (e.g. municipal) - national - regional (e.g. European Union) - and global (Scholte, 2019).

Human societies certainly fall in the category of complex systems, hence transcalarity can be seen as a valuable conceptual tool for gaining a deeper understanding of their operations. The larger urban and territorial scales, although fascinating to analyze and highly relevant in the discussion of necessary shifts in the context of the climate crisis, will not be an explicit part of this investigation of transcalarity, aside from some speculations into what consequences material cultures might have in larger geographical or global perspectives. Each scale has its own apparatuses, which have different requirements, but also require different tools of intervention and production. At political, geographical and territorial scale, architectural design is limited in effect, while the tools of socio-politics and economy, including policy making are more relevant. Therefore, through the tools of architectural design and some from microbiology, this thesis will mainly focus on the relationships across scales ranging from the building scale down to material composition.

In a period where architecture is collaborating with an array of other disciplines – such as material science, fabrication and manufacturing, structural engineering, building physics, social sciences, as well as increasingly microbiology and ecology – the ability to tackle the complexity of different scales becomes more relevant than before. Each of these fields has a main scalar focus, often tackling specific challenges that are within its operational reach. However, these all intersect in the realm of architecture, highlighting the need for transcalar approaches that can facilitate explicit integration. In a sense, transcalarity is about acknowledging and leveraging these scalar networks in the development of resilient and responsive architectural strategies.

3.1. On scale

Scale is a nuanced concept, and its precise meaning depends on the context in which it is used. The Cambridge dictionary offers various definitions – such as a numerical set for measurement or comparison, a ratio for representing the real size of something in models, or a descriptor for the magnitude of something (Cambridge Dictionary, n.d.). However, these fall short of capturing the richness of the term, especially in the context of the several areas of study in this work.

Firstly, a distinction between scale and size is necessary. While size denotes absolute, quantifiable dimensions, scale is about relational measures. Not necessarily defined by its physical extent, it is defined instead by the characteristics of the entities that constitute it, requiring a relationship between them (Horton, 2021).

Secondly, how scale is defined varies across different disciplines, each having its unique focus and application of the term. To arrive at a more nuanced definition of it, the disciplinary context is essential. As Horton points out, “the production of scales, for humans in particular, is thus inseparable from the differential functioning of disciplines, fields, and subfields. These knowledge domains come into focus through the resolving of specific material scales” (Horton, 2021, p. 15).

Horton (2021) identifies four frameworks, stemming from different disciplinary models for conceptualizing scale, each significant to the domain of architecture and particularly relevant to this study’s focus on transcalarity in architecture. These frameworks will be thus discussed in the context of this work.

The first framework Horton outlines is “Scale as Relational Ratio”. Originating from cartography, scale is here a way to map the environment on a two-dimensional surface, much smaller than the object of study. This notion has been crucial throughout the history of architecture, since most architectural projects were designed on paper. Various scales, from contextual, territorial surroundings at 1:1000-1:500 to detailed plans at 1:10-1:5, offer different levels of information and resolution. Just as no single cartographic scale can fully capture an environment, all architectural models lie (Southern, 2015). Therefore, multiple scales of architectural drawings and models are needed for a comprehensive representation.

However, material computational practices in contemporary architecture have generated shifts in the traditional use of scale. Working with bottom-up materiality, an understanding is formed that material properties cannot be fully abstracted. While industrial materials like concrete and steel come with standardized performance metrics, natural materials that grow to the specificity of their environment or are highly responsive require an effort to generalize their distinct characteristics. Plywood, for instance, involves layering wood slices with fibers oriented alternatively to achieve homogeneity. Moreover, when working with novel material systems or generatively integrating material behavior into the design, full-scale prototyping is necessary. This is because material properties, as natural phenomena, are not inherently scalable. They must be tested in their true scale, and this has been the practice in the work presented here, and one of the reasons for a research-by-design approach.

Furthermore, the development of digital fabrication technologies has altered the role of scaled drawings and representation in architecture. Drawings traditionally intended for builders and constructors are increasingly becoming obsolete as construction becomes automated. Instead of scaled drawings, machine-readable codes like G-code for 3d printing or rapid code for robotic construction are instead necessary to be produced from the architectural design.

Additionally, design processes that take place at separated scales such as 1:100 inherently restrict the extent of scalar integration as well as the resolution and number of interconnections that can be achieved. While the scale ratio between the architectural intention and its physical representation remains a key aspect of the design process, computational design methods allow for more complex relationships within data sets, thus offering alternative possibilities for working with architectural scale.

The second framework for understanding scale according to Horton is “Scale as absolute size domain”, a concept stemming from the field of physics. In this approach, specific domains of size are isolated, creating distinct territories that become generalized within the spatial continuum. For instance, electrons, bacteria, humans and stars, each occupy certain scales. As Horton states, these delineations often align with the technological tools we employ to observe them – whether it be a Scanning Electron Microscope (SEM), a magnifying glass, the human eye, or the Hubble Space Telescope. Each observational tool reveals different aspects of the same point in space. What defines a scale in this context is the types of relationships that can be observed among the entities within that scale, including the forces that acting on them, their abilities to be structured, or deform and differentiate (Horton, 2021).

In architecture, this conceptualization of scale is relevant for understanding the scalar structuring of building systems, through discretized elements. For example, a wall is as an extended load-bearing structure at one scale, whereas at a smaller scale, it is an aggregate of bricks, which at an even smaller scale is an aggregate of particles including silicon dioxide that are fused together through firing.

The production of multiple scales through differentiation can help understand the specific forces that take place at each level, thereby informing an integrated design process. Such an approach was adopted in the second paper of the dissertation (Goidea et al., 2022), where five scalar domains were defined to understand the varying parameters affecting each level, and then connected to map how they influence each other.

The third framework is “Scale as Compositional Structure,” a perspective on scale derived from the biological sciences (Horton, 2021). Here, function and size are intrinsically related. An increase in the size of an organism necessitates changes in function, design and distribution, a phenomenon effectively expressed by developmental biologist John Tyler Bonner: “(s)ize is volume, yet life’s activities require the appropriate surface to go with the volume and the result will be different shapes for different sizes” (Bonner, 2006). In living organisms, exchange of gases, nutrients and therefore blood, hemolymph, and fluid exchange systems for waste and other physiological processes need to reach throughout the volume of the organism.

The complexities of physiological processes become more pronounced as an organism increases in size, as fluids and gases need to circulate throughout the volume of the organism. Diffusion speed cannot increase with the speed of the flows, but through the choreographed distribution of these physiological functions through the organism. This is why for the functioning of an organism, the diffusion rates are maximized by increasing surface area (Turner, 2010).

In the context of biofabrication, these nuances in scaling become increasingly significant. Especially when working with microorganisms, living materials cannot be produced at architectural dimensions in an effective way through simple volumetric scaling, as one can do in casting concrete. The physiological needs must be accounted for, and this leads to complexities that make biofabrication at architectural scales challenging. Such considerations were central to the design approach in the project *Pulp Faction*, further described in Chapter 5, where generative design in combination with additive fabrication were employed to meet these complexities in scaling biofabrication.

The fourth framework, “Scale as homologous transformation”, is derived from the realm of pure mathematics. Unlike previous conceptions of scale that are grounded in empirical constraints, this perspective operates within a frictionless environment (Horton, 2021). Here, the notion of scale becomes paradoxically “scale-free”, as it maintains a constant relationship between parts and whole regardless of physical or social context. For instance, the scaling of a triangle keeps the same internal ratios and angles, it is perfectly analogous because no physical transactions are made. In this mathematical version, as perceived through the lenses of the other scalar concepts, the intricacies of scale as connected to its context become irrelevant.

However, this abstract scaling cannot be directly translated back into a real environment. The real world is rich with complexities – material constraints, social considerations, environmental factors – that don’t conform to a frictionless, scale-free mathematical model. Such attempts can be dangerous endeavors, such as the narrative of infinite growth on a limited sphere.

Horton’s frameworks for understanding scale are relevant for the ongoing discussion in this thesis, with a core takeaway that material and social context produces a variety of resistances in scaling. He emphasizes that scale is conceptualized differently across disciplines. This point is crucial, especially in the context of cross-disciplinary collaborations, such as between architecture and biology as studied here. The differing tacit knowledges and methodologies regarding scale can pose challenges for effective collaboration and deeper interdisciplinary engagements.

Another point of interest in Horton’s scalar frameworks is how they relate to the work with scales in this study. Mainly the second and third concepts of scale are used here, as the other two – working with scale in a representational manner, and scaling irrespective of the constraints of the environment that the scaled object sits in – are not aligned with the work presented here.

The second, absolute scale domain is useful in isolating specific forces and phenomena that are relevant at various scales, which helps integrate these in a transcalar approach. The third scalar model, derived from biological sciences, serves as a guiding framework for the development of biomaterial logic within architectural contexts. This is especially useful when dealing with complexities related to scaling biofabricated materials for architectural applications. When biofabricating fungal biocomposites, essentially each component becomes the scaling up to grow a “large” organism, so this process needs to incorporate the scalar complexities of physiological mechanisms.

3.2. Complex adaptive systems

The term complexity comes from Latin, meaning woven together, or entwined (Online Etymology Dictionary n.d.). As separating the strands of a braid makes the braid disappear, the elements that make up a complex system are not possible to separate; the system’s existence depends on the interaction between these (Larson, 2016).

The domain of complex systems is relevant to, and thus part of several disciplines, such as computer science, biology, mathematics, sociology, information theory, meteorology etc. Complex systems have been defined in several ways, such as “a system made up of a large number of parts that interact in a nonsimple way”, “a body theory about connections”, or “composed of interacting ‘agents’ following rules, exchanging influence with their local and global environments and altering the very environment they are responding to by virtue of their simple actions “ (Turner & Baker, 2019). Complex systems have distinct properties, such as emergence, adaptability, non-linearity, feedback loops and sensitivity to initial conditions.

This comes as an alternative to the reductionist framework employed in traditional biology. The reductionist method is dissecting systems into their constituent parts, which then are analyzed individually. This is exemplified by the claim made by Francis Crick: “The ultimate aim of the modern movement in biology is to explain all biology in terms of physics and chemistry” (1966, in Regenmortel, 2004). Although this approach has served science well in the past (Turner & Baker, 2019), it is today accepted that all the specificity of an organism cannot be understood only through the configuration of its individual molecules. The specificity, behavior and development in biology are resulting from the way these individual elements interact with each other (Regenmortel, 2004). This interaction is seen as a crucial aspect of the system, in the growing field of systems biology, which aims to connect its components within a scalar level as well as across scales (Tavassoly et al., 2018), employing computational tools to map this complexity. This approach is aligned to transcalarity, and has informed it. The explicit study of complexity has only entered the field of biology in the recent decades, due to the development of computation and thus of the possibility to understand and simulate biological networks using mathematical models (Emmeche; Alm & Arkin, in Regenmortel, 2004).

This is what emergence is referring to, not only as it pertains to biology, but in all complex systems: the phenomenon where behaviors, patterns and properties arise from simple interactions and adaptations of sub-parts at local level. Examples where emergence can be clearly identified are flocks of birds, colonies of termites and ants, cell metabolism etc. In such systems, small changes can have unpredictable effects, particularly when these interactions are non-linear[2].

This complexity can also be seen in how form and process are deeply interlinked in biological systems, as described by Turner (2010). In his physiology-centered perspective, the distinction between form and function is deceiving: “A living structure is not an object, but it is itself a process, just as much so as the function that takes place in it”. He exemplifies this through the termite mounds: “the mound is not a physical structure for the function of ventilation, it is itself the function of ventilation: it is embodied physiology” (Turner, 2010).

Homeostasis is the regulation of an internal environment to maintain stable conditions, both as a response to changes from within and without. As one of the main processes of physiological functioning, alongside biophysical and biochemical processes and communication between cells, homeostatic control mechanisms play an important role in the emergent behavior and complexity of biological systems.

This process operates at every scale, from cellular function to tissue and organ, up to entire organisms. The level where homeostasis takes place is informed by the scales above and below it, making it a transcalar process. For instance, the continuous reformation of bone demonstrates this: the forces experienced at a larger scale by the organism, transfer themselves into pulls of the muscle fibers, which influence micro adjustments at the cellular level in the bone, which in turn contributes to the emergent form and function of the bone tissue (Turner, 2010).

[2] Where the change in the output is not directly proportional to change in the input.

[3] These are secondary structure configurations of proteins, held in place by the alignment of hydrogen bonds.

3.3. Transcalarity in nature

I argue that the concept of transcalarity permeates life at every scale. Within living organisms, it can be observed in the formation and functioning of the main biological macromolecules: proteins, lipids, carbohydrates, and nucleic acids. These molecules interact to scale up in ways that have a massive impact on the complex processes of life.

The behavior of macromolecules in an organism can reveal a fascinating story of transcalarity. Besides functioning as signaling and energy storage molecules, lipids self-assemble into the lipid bilayer, which is the basis of cellular membrane. This process is so essential that the emergence of cellular life on Earth started with these as the early evolutionary step, as it has been hypothesized in the “Lipid World’”scenario (Segré et al., 2001).

The functioning of proteins and their countless configurations that perform highly specific tasks is also worth exploring as an illustration of transcalarity. Protein function can begin to be understood through four scalar levels (Fig. 2). The peptide backbone has a sequence of amino acids that ranges from few dozens to several thousands within a single molecule, and this forms the primary structure of the protein. This sequence is unique for every type of protein, determined by the gene that encodes for it. The secondary structure is determined by the hydrogen bonds between groups in the backbone, often resulting in repeating structures called *α-helices* and *β-sheets*[3]. The tertiary structure is the amalgamation of these *α-helices*, *β-sheets*, and the less regular chains detailing how they arrange and fold into a three-dimensional configuration. Finally, the quaternary structure is the assembly of multiple proteins, resulting in a complete conformation that behaves as a unit (Alberts et al., 2022). The positive and negative polarities internal to the molecules, the hydrogen forces and others bonds make the existence of proteins balance on the edge of stability. This enables them to have multiple structural states and undergo topological changes and thus participate in various complex interactions.

The protein molecules allow for most of the cellular functions, thus influencing several essential processes in cells. When they form enzymes, they decrease the activation energy necessary for chemical reactions to occur, speeding up metabolic reactions so that they happen at physiologically significant rates: from a reaction that would take

Fig. 2. The four scalar levels of protein structure and their organization. Source: Heim et al., 2010, p. 158.

three centuries to take place, when enzymes catalyze it, it takes one second instead. Without enzymes, chemical reactions would happen too slow to sustain life (Lewis & Stone, 2022). Other types of proteins serve as channels and pumps for the passage of molecules through the cell, as mechanical structures with moving parts, as motors transporting other molecules across long distances (*motor proteins*), transporting organelles (*kinesin*), untangling the DNA strands for replication (*topoisomerase*). Proteins are also the antibodies, toxins, hormones, elastic fibers, signal transductors etc. (Alberts et al., 2022) – all made from different configurations of just 20 amino acids.

Enzymes also guide metabolic pathways in organisms. These are incredibly complex, interconnected, self-regulated processes (Fig. 3), in the form of sequences of chemical reactions that take place within cells. Each pathway is a series of biochemical reactions, where the product of one reaction is the substrate for the subsequent one. Enzymes are the generators of this complex web of metabolic pathways, with many nodes of intersection and branching. The series of reactions in this network of pathways runs simultaneously, both creating products for other reactions as well as competing for them. Transcalarity can be observed in their operation, as proteins affect metabolic pathways that then regulate behaviors of cells, tissues, and ultimately the organism. By guiding chemical pathways in organisms, proteins are essential in cellular homeostasis, eventually scaling up to manage responses to external stimuli.

This also takes place in the reverse scalar order: transcalarity can be observed in how these pathways respond to external stimuli. For example, in the fight-or-flight response, the perception of danger by an organism triggers a series of physiological effects. At the organ level, the adrenal glands release a hormone called adrenaline (*epinephrine*) that travels through the bloodstream, reaching several target tissues. Entering the cells it reaches the lowest scalar level – at the molecular level, where epinephrine binds to specific receptors in the cell membrane, starting a cascade of reactions that ultimately leads to the breakdown of glycogen into glucose. This is then released from the liver into the bloodstream, providing the body with additional energy source, necessary to react to the perceived danger. At the same time, epinephrine influences the pacemaker cells in the heart, making them

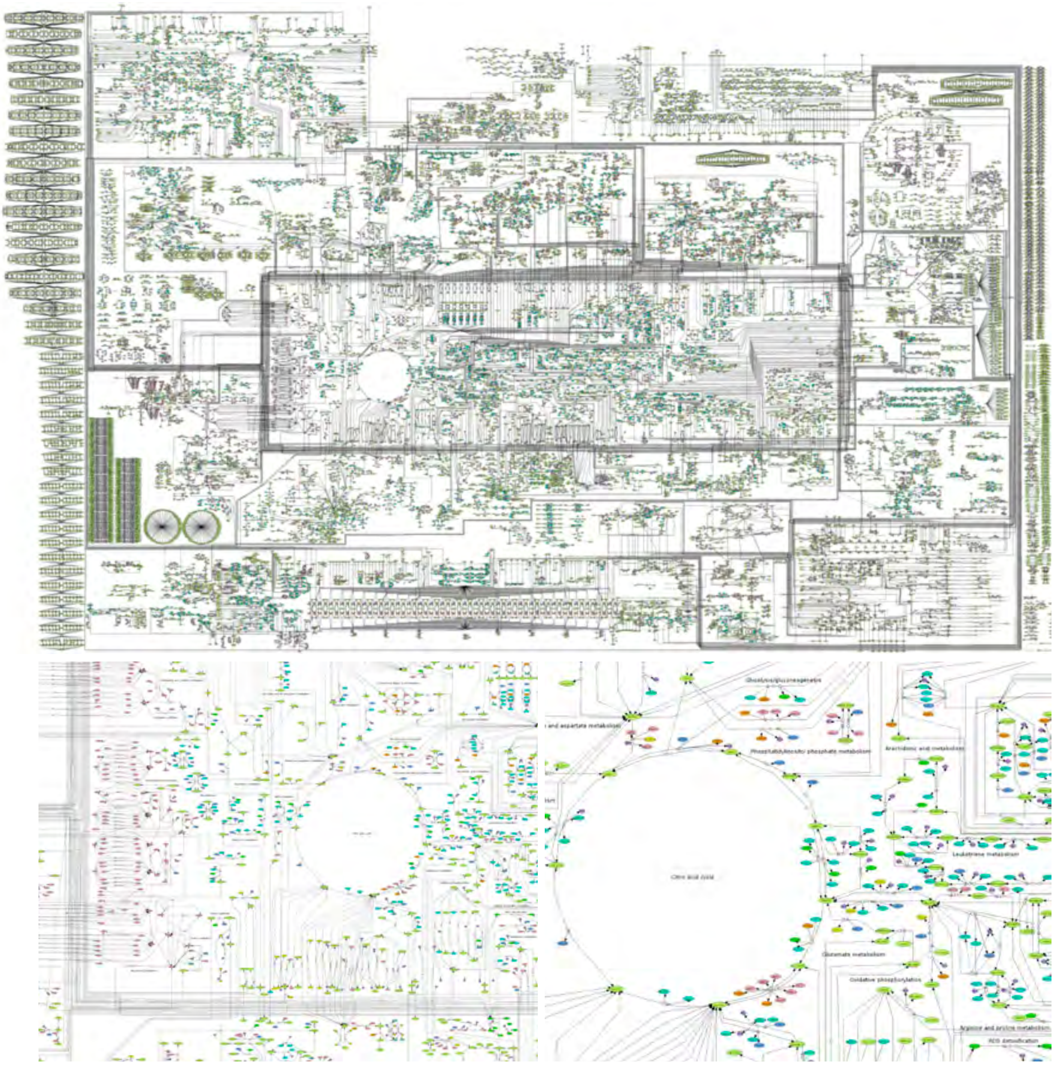


Fig. 3. Metabolic pathways. Figure shows interconnections between chemical reactions within and across cells. Source: Noronha et al., 2018.

beat faster, which results in energy and messaging molecules circulating through the body faster (Learn Genetics, 2023). Thus, a stimulus at the level of the organism triggers changes that span multiple scales down to the molecular level, illustrating how transcalarity is involved in the adaptive responses of the body. This integration and coordination between molecule, cell, tissue, organ, organism and environment is a prime example of scalar complexity. These interconnections enable the fine-tuned regulation of biological processes, making it possible for organisms to adapt and thrive in diverse conditions.

Ecosystems, too, exemplify scalar interconnectedness. As Hirata (2016) describes, “The living world we inhabit, from the microlevel — a protein, say — to the macro level — a jungle, perhaps — is an interwoven or entangled mesh of order. From an incipient cause, one living thing becomes entangled with another, and then another thing tangles with the previous, and so on”. This resulting “order of refined coexistence” observed in natural systems holds significant relevance for the design experiments discussed in this work.

The stability of ecosystems is dependent on not only the number of connections within it, but also on the nature of these connections. Thus, ecological systems can be seen as entangled, transcalar networks of interaction, incorporating a view beyond the reductionist perspective of a sum of individual organisms or species. This view is embraced by Tsing et al. (2017), using the term *monsters* to describe the power of this entanglement: manifested through the wonders of symbiosis, as well as their flip side, when these entanglements disrupted, the threats of ecological disruption through positive feedback loops. They warn “against the conceit of the individual”, calling for the acknowledgment that “monsters highlight symbiosis, the enfolding of bodies within bodies within bodies in evolution and in every ecological niche” (Tsing et al., 2017).

Growth, response, adaptation – are functions of the biological world, and arguably these are possible due to their inherent transcalarity, as the ability of living systems to adapt, change and transform requires navigating through several scales. Interconnectedness drives the remarkable complexity of life at multiple scales of organization. From the smallest building blocks to the most complex organisms, and then their communities operating interconnectedly within ecosystems, the interplay of different levels of organization serves as the basis for the rich diversity and specificity of life on Earth, and calls for being placed at the core of the design efforts in this body of work.

3.4. Temporal scales

The traditional view of successful architecture often prioritizes notions of “timelessness” and “permanence,” as highlighted by the recurring themes in Pritzker Prize awards (Heynen, 2012). This view celebrates architecture as an enduring monument to human ingenuity, of taming matter and capturing the values of a culture and a point in time for generations to come. It is rooted in an anthropocentric perspective that praises the individual genius who leaves historical marks.

These values are in line with a material culture founded on extraction of finite resources, which at the same time is at odds with the current pace of change. Yusoff (2017) points to this “temporal buckling”, and how through the lens of the Anthropocene is essential to shift temporalities, in addition to addressing spatial and material transformations:

> We might imagine the term “architecture” to refer to the organization of the material structures of space and its temporal patterning; or, how the material mediation of space orders a specific temporal indexing. These new empirics of sedimentation, of rapidly destratifying and restratifying social, economic, and mineral practices, are rearranging the global dynamics of the bio and geosphere. This suggests that the old artifacts of Earth that constituted the imagination of global-world-space are overly reliant on a stable material foundation and therefore a temporal location. In this sense, the Anthropocene as a new rendering of time, subjectivity and agency announces both a break in and consolidation of modernity’s temporal arc. The city, as an ever-expanding urban fossil, is enacting a temporal buckling in its allegiance to the “now” in the form of its on-going contribution to a hominid geology with a duration far in excess of contemporary visions of disposability, newness and change. (para. 3)

This current construction paradigm often justifies high initial material and energy costs by the expectation of long-term usage (Andréen & Goidea, 2022). But as human societies are constantly evolving – as complex systems do, the perceived permanence of these structures often comes at a cost too high, particularly when they outlive their usefulness long before their material lifespan is exhausted. Many buildings are prematurely demolished due to various reasons, such as changing land values and zoning policies, inabilities to meet current local social needs, global climate change, or the decay of non-structural but still important parts of the building (O’Connor, 2004). Short-lived utility is starkly reflected in several studies on the lifespan of buildings: in the UK 46% of demolished buildings had a life span of 11-32 years (DTZ Pieda Consulting in O’Connor, 2004), while it has been found that in Japan the average life span of office buildings lies in between 23-41 years (Yashiro et al. in O’Connor, 2004).

An alternative may be found in the approaches to architectural timescales — and their materialities — of the vernacular human and animal-built structures. Such construction centers collaboration, hyper-local resources, adaptability, and even impermanence, providing a stark contrast to the “prevalent paradigm built on permanence and stability” (Ramsgaard Thomsen, 2022).

Given the reality of an urban landscape that experiences a rate of material turnover surpassing the decay timescales of materials, our perspective on the environmental impact of materials such as wood needs re-evaluation. These are seen as less durable and therefore, sometimes measured to have a higher environmental cost in comparison to e.g. concrete or steel. In this regard, it has to be taken into consideration that the environmental footprint of wood is generally inflated by the inclusion of the impact of a *replacement building* in the analysis of their (supposedly short) life-cycle (O’Connor, 2004).

The pressing realities of rapid change and environmental impact point to the necessity for strategies that incorporate time scales into the conception of architecture. This could be manifested through a shift towards practices that are more adaptive, localized, even impermanent – when using low impact materials, that account for maintenance, upkeep, and circularity, to better align with the changing rhythms and needs of society. The resulting architecture aims to be sensitive to the multiple scales of temporalities that exist within it, from functional changes, short-term adaptations to fluctuating weather conditions, to the geological eras impacted by the current modes of operation.

3.5. Transcalarity precedents

This section explores several precedents for the concept of transcalarity as developed in this work. As scale is an important issue in the realization of architecture, it has been addressed numerous times throughout history, and sometimes explicitly emphasizing the interconnection between its constituting scales.

One such example is the notion of *intricacy*, by Greg Lynn: “Instead of puncturing volumetric minimalism with discrete details, intricacy implies all over complexity without recourse to compositional contrast. Intricacy occurs where macro- and micro- scales of components are interwoven and intertwined“ (Greg Lynn, 2003).

Another example of an overall system that integrates scales is the *co-design* approach (Knippers et al., 2021). Initially developed at ICD IKTE in the context of large-scale coreless robotic fibre wound structures, it was later applied to several other fabrication systems. The *co-design* methodology was created to facilitate the linkage and transfer of information across various domains and disciplines, an action that often carries scalar implications. The method is divided into five areas, A to E. Although not explicitly assigned a scale, these areas inherently exhibit a scale focus; for instance, area D entails a wider scale and social context of the building, while the material within area C pertains to a much smaller scale. Additionally, they emphasize the need for integration between these domains, both by developing them in parallel, and by having feedback loops between them. This approach is implemented through computational design and fabrication tools, such as simulation, cyber-physical systems and machine learning (Knippers et al., 2021).

An example on a more political sphere is the term *transscalarity*, used by Andrés Jaque (2022) to refer to the exploration of the entanglement of life, bodies, technologies, and environment. Jaque highlights *transscalarity* through an example on how the process of architectural detailing has the capacity to serve as a mechanism for socio-territorial reconfiguration. He exemplifies this through the case of ultra-clear glass, a prevalent material in architecture. The specific silica required to produce ultra-clear glass is only available in a few locations around the world, including a site in Ottawa, Illinois. The unique microstructure of this particular silica variant is porous, allowing water to permeate through the rock formations in which it is embedded. This specific attribute of the silica-rich environment has fostered a habitat abundant in species diversity, and historically, the area was recognized as a sacred hunting ground by certain Native American tribes. The same quality of porosity that contributes to the ecological richness of this area also results in the production of high-grade glass, capitalized in luxury retail outlets and residential properties (Jaque, 2022).

The extraction of this material for such applications carries heavy ecological and political consequences. This frames a question raised in Jaque's work that is relevant in this thesis: How should we design knowing that architectural matters at the micro-scale, such as the choice of a specific type of glass, reverberate at broader scales, impacting ecosystems and socio-political landscapes? He emphasizes the importance of scale in contemporary politics, suggesting that architects need to develop new tools to navigate the complexities of scale. Designing while consciously integrating transcalarity can produce architecture more in balance with its environment.

An elaboration of three frameworks specifically addressing the interconnection between scales in architectural design are described in the following sections, and these bear a closer relevance to the sub-topics in the present study on transcalarity.

3.5.1. Multi-scale modeling

Multi-scale modeling (Nicholas et al., 2016) is a precursor to the notion of transcalarity in architecture. Originating in computational design, it is a strategy for addressing design at different scales simultaneously. As they outline, this approach breaks down a design problem into "distinct

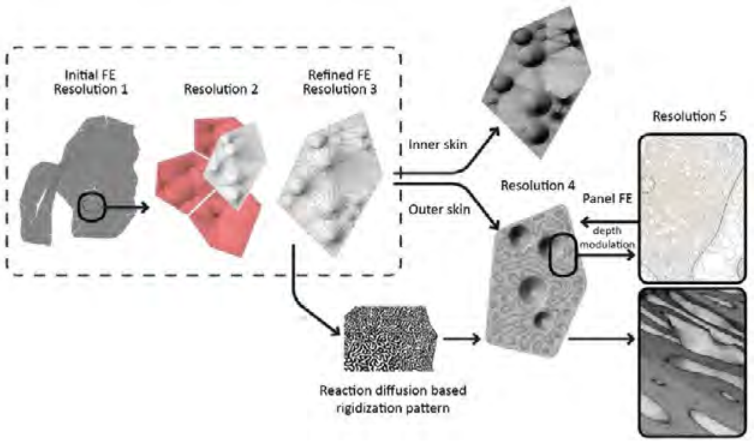


Fig. 4. Multi-scalar modeling. Information flow across different scalar resolutions. Source: Nicholas et al., 2016, p. 312.

but interdependent models according to scales or frameworks" (Nicholas et al., 2016) and uses custom techniques to facilitate the transfer of information between these scales (Fig. 4).

Multi-scale modeling addresses this through establishing a continuous digital workflow across three core scales: micro (material), meso (component or panel), and macro (overall structure). This methodology was employed in the design and fabrication of *StressedSkins*, a self-supporting structure made from thin steel sheets articulated through robotic incremental sheet forming.

Unlike traditional architectural modeling, which often focuses on one scale at a time, from the overall global design gradually zooming in, while assuming homogeneity across other scales, this methodology employs nested algorithms at different resolutions. These are interdependent, as the output of one serves as the input for another. This hierarchical relationship is mapped, with each level addressing distinct requirements within the same model. Given that the Grasshopper tree structure – more akin to a dictionary – cannot store these dependencies, a custom class has been employed to maintain the data connections of the nodes in the hierarchy. Adaptive subdivision was used to minimize computational costs, allowing for the local detailing of information only where necessary. Importantly, this methodology ensures that potential failures at various scales — such as buckling at larger structural scale and at the component scale during assembly and use, as well as buckling and tearing of the material during fabrication — are preemptively addressed (Nicholas et al., 2016).

While *multi-scale modeling* and transcalarity share similarities in their intent to integrate different scales, there are differences. *Multi-scale modeling* primarily focuses on the computational environment. On the other hand, transcalarity serves as a broader conceptual framework that extends beyond the computational aspects, emphasizing interconnectedness and dependencies across various scales and fields. Nevertheless, the multi-scale approach provides valuable insights and methodologies that can be integrated into the larger conversation regarding transcalarity, underlining the need for computational models to address this complex issue in architectural design.

3.5.2. Material ecology

Material ecology defines a design framework that proposes informed relations between buildings, systems, and their environment (Oxman, 2010). It refers to the integration of processes into design that employ material logic, computational form-finding and digital fabrication, while being environmentally informed. This framework is proposed as an alternative to the logic of assembling parts with discrete functions, a consequence of modernistic standardization of components: “where homogeneous materials are formed into pre-defined shapes at the service of predetermined functions” (Oxman et al., 2015, p. 1).

The interactions between the object and its environment are complex, connecting at multiple levels and through a spectrum of variables. Oxman et al. (2015) argue that the dimensionality of the environment is much more complex than the one of the conventional design space. This difference often results in a dimensional mismatch, and an incomplete mapping of these connections. They argue that this then leads to an ecological mismatch, where designed objects are not fully fitting in their surrounding ecology. They suggest instead that the *material ecology* approach increases the dimensionality of the design space through performative materials, high resolution and articulation through digital manufacturing and complex computational algorithms. (Oxman et al., 2015).

The work within the *material ecology* context is positioned at the intersection of biology, material development, and digital design and fabrication, which overlaps with the current study. Several of the works involve additive manufacturing of biocomposites, such as *Aquahoja I* and *II*, extruded with graded chitinous materials derived from shrimp shells. *Silk Pavilion* employs directly silkworms as “natural 3d printers” for the secondary structure of a canopy, while responding to environmental inputs such as light and heat (Antonelli et al., 2020).

Just as transcalarity involves an exploration of interconnected scales – ranging from material properties to ecological systems – *material ecology* extends the dimensional range of design, facilitating more intricate relations between scales. This expansion mirrors the transcalar notion of a multi-dimensional design space, where the parameters are not just diverse but strongly interconnected. Along transcalarity, *material ecology* can inform and enrich design practices, particularly in contexts that involve biodesign or adaptive systems.

3.5.3. Architectured heterogeneous materials

Bouazis et al. (2008) also address the issue of integrating transcalarity into designed structures, although using a different terminology. They explain two main distinct approaches in designing material performance: that of the engineer and that of the metallurgist. In mechanics, it is common to assume a homogeneous material of predictable behavior. The engineer designs the overall geometry of a component to perform in a specific way, based on known material. On the other end of the scalar spectrum, the metallurgist solves the performance problem from the microstructural level. Through controlling the length scale of the interatomic bonding, by changing the composition in the alloys – the intrinsic properties are refined to offer new performances. Bouazis et al. (2008) propose a synthesis of these approaches, where shape optimization and graded microstructures combined form a new category of performative *architectured heterogeneous materials*.

Bouazis et al. refer to this interface between the two scales as "architecture", similar to the role of transcalarity in this context, but with a focus on material science. Their approach suggests that new methods of processing are necessary to enable this kind of scalar organization. This is an interesting perspective, as the design of performances is explained through the lens of scalar interaction, albeit from a different disciplinary viewpoint.

This utilizes the tools of material science, where properties such as yield stress, toughness, ductility, magnetic properties, acoustic absorption can be addressed. These are done through alloys, composite materials such as where the metal matrix contains sufficient amounts of covalently or ionically linked particles like ceramics, and through scale refinement. On the other hand, engineers address issues such as stiffness through larger scale interventions, such as global shape optimization, while assuming a homogeneous material. They give an example on how a square beam can be replaced by an I-beam to improve the stiffness, with the same material, and same quantity, just by the formal disposition. Another example is the stiffening of a plate through corrugation (Bouazis et al., 2008).

However, both of these approaches have limitations when the requirements are multifunctional or conflicting. For instance, scale refinement techniques have downsides in thermal equilibrium, and modifications through alloys and composites decrease the damage tolerance of the material (Bouazis et al., 2008). A key argument they pose, highly relevant to this thesis, is that such a multicriteria challenge cannot be addressed at a single scale only.

This study highlights the benefit of an integrated approach that reconciles the methodologies of physical metallurgy and mechanics to address challenges that exist at different scales. This cross-disciplinary strategy seeks to articulate an intermediate length scale, informed by both macroscopic engineering and microscopic material science, to create multifunctional materials and structures. This not only underscores the significance of understanding how different disciplines function at various scales but also emphasizes the efficacy of tackling specific issues at appropriate scales. This integrated methodology shares scope with the design of graded metamaterials, highlighting the broader applicability of transcalar frameworks in diverse design fields.

Metallurgy offers insights into transcalarity through an additional perspective, presented by De Landa (1995). He highlights complex behaviors in material systems that are inorganic. Here, emergent properties like strength and toughness result from the interaction of sub-components. For example, ductile materials resist breakage as a result of the complex dynamics of cracks at microscale. Allowing imperfections within the material can have benefits. As dislocations move, they trap energy locally, and thus do not transmit the energy that a fracture requires in order to spread (De Landa, 1995).

Naturally occurring metals contain impurities that affect their mechanical properties. Over the last two centuries, industrial materials such as steel have been standardized for consistent quality and predictable behavior, which have been essential for the mass production's economies of scale (De Landa, 1995). The design and manufacturing processes have also been streamlined by this homogenization, for an easier management of segmented steps. Particularly, mild steel can be seen as a material that simplifies skill requirements: “at a higher mental level, the design process becomes a good deal easier and more foolproof by the use of a ductile, isotropic, and practically uniform material [...].

The design of many components, [...] can be reduced to a routine that can be looked up in handbooks” (Gordon, 1988, pp. 135).

While this standardization furthered scientific advancements, it came with compromises. However, perhaps now is the time to reassess these economies, considering resource implications and the potential of embracing variation. Intrinsically heterogeneous materials, such as the biomaterials addressed in this thesis, as well as local, unprocessed materials on one hand and composite materials on the other, do not have homogeneous, predictable properties. The benefit of these is that such materials can be prescribed not only to suit individual structures, but specific areas within a structure (Gordon, 1988).

De Landa’s study of metallurgy emphasizes that all complex systems, whether biotic or abiotic, are generative when they include non-linear interactions, allow energy flow, and operate in a state far from equilibrium. Harnessing these traits by working with their inherent complexity can yield desirable effects. Interestingly, this mirrors Turner’s (2010) statement on homeostasis in living systems regarding the need for non-equilibrium states for effective physiological processes.

De Landa adds that the willingness to not suppress variation, but instead to use it as a creative force should be one of the challenges to be faced by innovation in design: “the question is not whether we achieved some efficiencies through [...] standardization. We did. The problem is that in the process we came to view heterogeneity and variation as something to be avoided, as something pathological to be cured or uprooted since it endangered the unity [...]” (De Landa, 1995, para. 21).

Ultimately, design should not be separating form and structure from innate material properties. This aligns with the material computation framework, as well as the architectured heterogeneous materials.

3.6. Transcalarity in architecture

Architecture is a discipline of synthesis, sitting at the intersection of and having to negotiate different constraints from different agents and domains. This negotiation takes place at different scales, which traditionally range from the selection of appropriate building materials and resolving building details to designing human and urban spaces.

The recent developments in tools for visualization and analysis, from scanning electron microscopy to satellite imagery have shed light on countless processes that take place at different scales than what is observable at the human scale, with the naked eye. This has also revealed how both the micro scale and the planetary scale are impacted by human activities, including the agency of architecture and its material and socio-spatial effects. Previously hard to detect changes are now very visible – such as shrinking ice caps, deforestation, the footprint of the erection of buildings all over the globe, and the thinning biodiversity in essential microbial ecosystems. These show the effects of human activity – and architectural activity – on other scales than those where architects typically operate. Therefore, including the "scales beyond" in the process of making architecture has never been easier, or more urgent.

An architectural understanding of transcalarity emphasizes that architecture is not an independent act but an intricately interconnected practice. As Philp Beesley (2006) suggests, this confluence of disciplines led to a practice capable of analyzing and affecting nature, both positively and negatively, across multiple scales and dimensions. Ramsgaard Thomsen (2022) elaborates on this by stating that the scales of material engagement are not merely sequential but are interconnected and mutually influencing. While material considerations remain critical in this body of work, the concept of transcalarity extends beyond these. It encompasses elements such as large-scale form-finding, global value chains, and the flow of information across digital and physical platforms.

To conclude, architectural practice is increasingly visible as a complex cross-disciplinary negotiation between different scales, agents, and systems. As Myers et al. (2012) aptly put it, designers are not simply creators of individual objects but are initiators of multi-scalar systems that range from resource collection to consumption and disposal. Architectural practice needs to undergo a paradigm shift, transitioning from the mere act of space-making to a far more complex process of systems thinking. This expansive perspective, influenced by transcalarity, necessitates that architects consider the full spectrum of their influence, ranging from microscopic material properties to planetary ecological impacts.

In physics the truth is rarely perfectly clear, and that is certainly universally the case in human affairs. Hence, what is not surrounded by uncertainty cannot be the truth.

- Richard Feynman, 1976

4. Methodology

The design experiments presented in this thesis span multiple disciplines, primarily architecture and design, fabrication, material development, and microbiology. Each of these fields involve their own methods, which is both by convention and from necessity. The cross-disciplinary nature of the investigations stems from the interdependence of these research areas in the conducted experiments and brings the implication that the developments must not only move between these methods but hybridize and adapt them.

Because of this, the overall methodological framework is research by design, which is particularly suited for explorations of complex, interdependent systems united by a material outcome. It is a method of exploration and knowledge production that relies on constant making and iteration of physical and digital evidence in the form of prototypes and experiments. The outcome is not necessarily to be seen as fully finished proposals, but more of an indicative map of possibilities. Where the work ends, an opportunity emerges to further explore the presented hypotheses, either through new transdisciplinary iterations or in more traditional disciplinary modes.

4.1. Research by design in an exploratory approach

Research by design can be defined as research with project-grounded methods (Findeli et al., 2008). This means that the study is not subject to an already existing or external methodological protocol, but develops its own frames, successive problem definitions, scope, and epistemological depth with regards to how the project proceeds, and how experiences emerge from it. For this to work, a demand is that the project-driven research must aspire to reach novel knowledge regarding research topic, theory, and methods relevant for the domain of investigation. In this thesis, that domain is ultimately architectural design, and more specifically, design that combines computational and biological modes of production.

Although the research by design approach allowed relatively open-ended research questions, they had to reach beyond product development or isolated design tasks. Research by design, and its kin notions *research through design*, *project-based research*, or *design-led research*, was developed as a concept and method in response to an ever-increasing amount of cross-disciplinary research and practices that made it hard to maintain the relevance of strictly separate disciplinary means of investigation within art and design (Frayling, 1993). It also emphasized the role of the artifact as the place where “thinking is embodied”, e.g. where visually expressed results, as well as verbally communicated ones, can be regarded as forms of knowledge (Frayling, 1993). Even though research by design can be used by other disciplines than the strictly design-related ones, in this context, the notion of research by design is employed to enable the exploratory possibility of advancing cross-disciplinary approaches with a focus on design. This is achieved through exploring, reasoning, shaping, adjusting, and changing the design of architectural articulation and performance.

The projects carried out in the context of this thesis rely on the ability of the design practice to move between problem spaces. Here research by design as a methodology allows for integration of different disciplines, as stated by Ramsgaard Thomsen (2009): “the design proposal leaps between different modes of rationality relating its concerns with for instance the scale of the city, sociality, programme, construction, material and environment”. Through this methodology different constraints and modes of operation from different disciplines and scales can be negotiated.

In a theoretical framework linking biology, digital design-fabrication, and material research, three design experiments are here employed to take on different challenges regarding the development of algorithms, material components and overall performance. These challenges are iteratively undertaken through probes, prototypes, and demonstrators (Ramsgaard Thomsen & Tamke, 2016). Probes, prototypes, and demonstrators appear and re-appear in different evaluative moments of the research project, related to what can be labeled pre-design, design and post-design phases (Roggema, 2017). In line with the terminology of Ramsgaard Thomsen & Tamke, a demonstrator is here seen as a full-scale architectural artifact "not as a complete architectural edifice engaging the breadth of architectural concern, but rather as bracketed by its particular investigation" (Ramsgaard Thomsen & Tamke, 2016, p. 50).

Material prototypes usually precede the demonstrator and isolate specific inquiries while also conveying an architectural vision (Ramsgaard Thomsen & Tamke, 2016). Material evidence, being a recurrent means of testing and evaluation in the projects of the thesis, can thus actually be seen as means of communication, and will be discussed as such in the last chapter.

A distinction between this type of material evidence and models is in order here. The main purpose of material artifacts as employed here is not representational, but to test different aspects of material performance, structure, construction logic, fabrication, assembly, etc. This approach aligns with Menges's (2014) statement that material and morphological traits are continuously refined through feedback loops that consider the interaction of the system with static forces, thermodynamics, acoustics, and light. Here, material experimentation is key, as materiality is a critical element linking different scales, disciplinary frameworks, and performances. However, these artifacts, although not becoming architecture, they represent more than objects. As Ramsgaard Thomsen and Tamke (2016) noted, through spatial engagement, they hint at dimensions beyond their technical, structural, or material investigations, thus becoming architectural.

Throughout most of the research, digital models, especially generative algorithms, have been utilized. These models were adjusted to account for material characteristics as well as constraints and variables in fabrication. The focus was on an iterative process that explored various design options, through a tight, non-linear interaction between the digital and physical prototyping (which included biological considerations). The physical making of these prototypes brought to light new insights and concerns related to fabrication, reinforcing the validity of a research by design approach.

4.2. Research by design in biology and biofabrication

Engaging methodologically with biological matter inevitably entails grappling with significant complexity, which raises issues related to reductionism and non-reductionism. This also implies that microbiological requirements and resulting fabrication constraints emerge, and these lie outside of traditional domains of concern in architecture.

Systems thinking is an approach to analysis that focuses on the way that the constituent parts of a system interrelate, how systems work over time, and how they are nested within the context of larger systems. This can be used to tackle complex or *wicked* problems, such as the ones in design, and even more so when addressing biodesign and biofabrication. However, while systems thinking aids the understanding of interconnection within natural systems, through the lens of transcalarity these multi-scalar interactions and their implications are integrated in the design process.

Hence, to design in a way that intentionally exhibits characteristics of natural systems is a more difficult task than the more surface-level biomimetics. “Design that sets out to deliberately achieve the qualities that actually generate these [natural] forms – adaptability, efficiency and interdependence – is infinitely more complex, demanding observational tools and experimental methods of the life sciences” (Myers et al., 2012).

Biofabrication was a central aspect of the first design experiment, *Pulp Faction*. From this followed that a considerable part of the research was in the field of microbiology, with its own methodologies, and which are remote from the typical skillset and approach conventionally found in architecture. These specific methods are largely centered around rigorous protocols[4] that guide how experiments are conducted. The research in this project relied not only on following established protocols, but also developing new ones that stemmed from the requirements and demands of other fields: architecture and digital fabrication. Perhaps the most significant of these was the move towards larger scales than those usually addressed in the field of microbiology (where the petri dish[5] is on the higher scalar range). Through research by design, the results from these experiments were integrated with previously available data, or data generated through other methods, and the protocols for biofabrication were refined. This process is accounted for in more detail in the chapter and visual journal below describing this project.

Since transcalarity includes the aspects of material agency and adaptability as described above, and furthermore adds the specific aspect of influences across spatial and temporal domains, it can be open-endedly investigated as a complex matter in research by design approaches. To more explicitly render such transition issues, the three sections dedicated to the specific design experiments will separately comment on the issue of transcalarity.

4.3. A note on aesthetics

This complexity of working with natural systems has had an impact on what is labeled as aesthetics, as biological materials not only have their own character, but also their own agentic possibilities, affecting and being affected by a variety of domains.

The relationship between methodology and aesthetics is more derivative when focusing on material performance and computational adaptation. Instead of adhering to predefined aesthetic norms, the projects in this thesis are largely a result of their inherent conditions. Considerations of materiality, biological characteristics, and computational possibilities, have all contributed to the creation of three architectural artifacts: a column, a wall, and a spatial framework. While research by design does not aim to eliminate the influence of the

[4] In natural science research, protocols define a step by step method for conducting an experiment or study (Hinkelmann & Kempthorne, 1994).

[5] A shallow circular dish, usually transparent, used for the culture of microorganisms.

researcher's design choices, the parameters have shaped the result in a bottom-up manner to a large extent, and the researcher influences the outcome in the choice and formulation of processes and methods, interacting with the agency of the systems they design. Furthermore, certain elements such as boundary, size, and the choice of cross-disciplinary connections are inevitably shaped by the researcher's input and decisions.

As a result, the visual quality of these design experiments is primarily conditioned by diverse factors such as surface-to-volume ratio, affordances relating humans to other species, and inter-agentic material and biological possibilities. This is aligned with Yusoff's (2017) perspective on aesthetics as a critical engagement with geologic forces and the Anthropocene. Rather than prioritizing visual presentation, Yusoff highlights the role of aesthetics as an investigative tool for examining complex ecological relationships, thereby pushing the conceptual boundaries of agency, materiality, and interconnectedness in the Anthropocene.

Therefore, following Yusoff's approach to aesthetics as an outcome of action, rather than only visual representation, the role of architecture shifts in this study from visual to behavioral. What emerges is an aesthetics of *consequences*, where the aesthetic qualities are seen as emergent properties of the processes and methods that shape them.

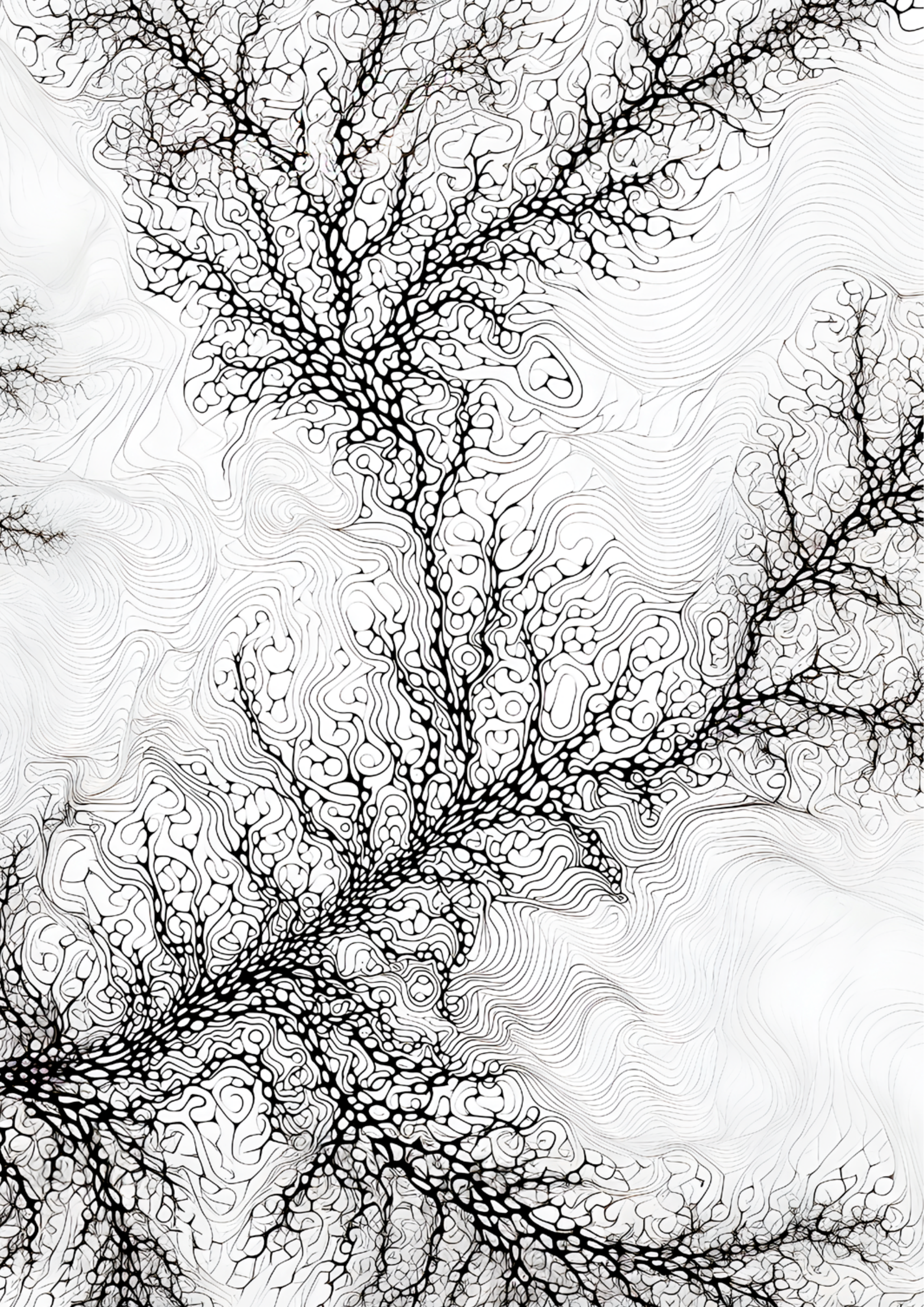
4.4. Design experiments

The design experiments in this dissertation attempt to answer the challenge of integrating biological principles in architecture through different design approaches. There are three design experiments in the dissertation, and they each have different roles and perspectives in the overall exploration of transcalar design. These sub-projects vary in their scope and extent: *Pulp Faction* had the most significant allocation of time and resources, followed by *Meristem Wall*, while the ongoing project *Swarm Materialization* received considerably less than the others. However, all of them represent important aspects in the exploration of transcalarity.

Each design experiment was structured around a distinct biological reference and utilized a different toolset. Nonetheless, each served to develop a framework that explores a conscious application of transcalarity.

Pulp Faction is a project that investigated biofabrication in a computational design context. It concluded in the making of the prototype *Protomycokion*, a column 3d printed from a wood and living fungus composite. This project sits at the complex intersection of architecture, digital fabrication and a live organism, and investigated how computational techniques are used to mediate and connect these aspects. *Meristem Wall* is an exploration of functional integration and self organization in a building envelope. It explored the potentials of architectural metamaterials and performative geometries through high geometric resolutions, as interfaces between environments. *Swarm Materialization* is a project that explored the connections between self organization, fabrication, and material behavior in a nonlinear manner. This is explored through a discrete, nonsequential additive manufacturing of clay depositions forming spatial structures that are dictated by and dictate a swarm algorithm.

The following three chapters are dedicated to each of the three design experiments. In the discussion chapter that follows each of the three project descriptions, I elaborate on the concept of transcalarity as it is expressed, tested, and resolved through these design experiments. Every project is distinct, made with different additive technologies, utilizing diverse material systems, and targeting specific performances. Consequently, each poses its own aims and research questions, distinct from the others. Yet, beyond their reliance on additive fabrication and computational design techniques, they all draw parallels to biological systems that are investigated through the prism of transcalarity.



It will be soft and hairy.

- Salvador Dali,
on the future of architecture
in response to Le Corbusier

5. Pulp Faction

This project investigates the making of new materials through biofabrication with fungal composites using computational tools for design and fabrication. The project stretches across scales that are defined on one extreme by the microscopic nature of the fungal organism and on the other by architectural space and function. Computational tools and digital fabrication are explicitly used to bridge these scales together.

The research project has concluded with a demonstrator called *Protomycokion*, a two meter high column. The research has covered material composition, digital fabrication processes, fungal selection and steering, biofabrication protocol design, computational design and assembly. The project aimed to explore the possibilities and limitations of 3d printed fungal biocomposites, determining if they can be scaled to architectural component scales, and identifying the required microbiological, design, and fabrication protocols required to span these scales.

5.1. Fungus comb as a biological model

Before going further into the specific methods and how *Pulp Faction* explores transcalarity, it is worth elaborating on the transcalarity inherent in its biological model. The research is based on a naturally occurring precedent of fungal-lignocellulosic biocomposite, called a fungus comb. This is a structure emerging from the symbiosis between certain species of termites and fungi, a structure that feeds both fungi and termites, while presenting several connections between its constituting scales. It is built through an additive process, constructed one deposition at a time by the termites and transformed chemically by the fungus. Its resulting geometry, both at local and global scale negotiates the growth needs at a cellular level of the fungus, the scale of digestion for both organisms, access for deposition and feeding for the termites, oxygenation, overall structural needs of self-support.

This symbiosis between a genus of termites called Macrotermes and a fungus, Termitomyces, has existed for over 30 million years (Wisselink et al., 2020). As the termites don't have the enzymes in their digestive tracks to break down cellulose and lignin, they have instead evolved to rely on the Termitomyces fungus for their digestion. Inside the mounds, the termites are building dedicated chambers in which the fungus lives and where sufficient humidity for the fungus' metabolism is maintained. Here, the termites bring plant matter scavenged from outside the mound and with it construct fungal structures called fungus combs. The fungus grows through these structures, slowly breaking down the plant fibers into sugars. This slow decomposition of the fungus is beneficial for the termites as it allows them the time to consume the sugars as well. On the other side of the symbiosis, the termites are providing the plant substrate for the fungus as well as keeping a clean environment in the chambers, free of other fungal species and bacteria, that would constitute a problem for the non-competitive Termitomyces. Perhaps as they have evolved through this symbiosis, this fungal species can only be found living inside the active mounds of Macrotermes (Wisselink et al., 2020).

Pulp Faction builds on a pilot research study by our research group. This research originated from the fungal comb structure and our fascination with its form, function, and morphogenesis. Of apparent relevance to architecture are its material properties. When dried out, these have interesting properties, such as a high strength to weight ratio, hydrophobicity, and moisture absorption capabilities – believed to play a role in the termite mounds' humidity regulation mechanism (Arshad & Schnitzer, 1987). Introducing these properties into a new architectural material had been of central interest in the project. However, essential here is how material properties, process and geometry are interlinked, and how this can be read through the lens of transcalarity relevant in architecture, beyond simply adding another entry to the library of architectural materials.

The geometry of fungal combs is striking for its complexity. Arguably, this is a clear example of how form and process are deeply interlinked, as is described by Turner (2010). The complex balance of cavities and bridges that create the comb is in part due to the need of the termites to reach and deposit the freshly harvested plant matter for decomposition, as well as to reach and consume the already decomposed fibers. This however doesn't fully explain the porous geometry, as they could still be deposited on one end and harvested at the other even if in a block structure. The reason we have hypothesized is that the fungus comb, as a product of a symbiosis, isn't solely adhering by the construction and feeding rules of the termites, but also of the needs of the fungus. And since the fungus is aerobic, the more access to oxygen it has, the more plant matter it will be able to convert into nutrients for both itself and the termites.

The combs sparked an interest in their potential role as architectural materials. The ensuing research project started with the following question: What methods can be elaborated and employed for additive fabrication at architectural scale application based on the fungal comb? The link between fungal growth and its need of oxygen was central to the translation of the material system into architectural materials and resulted in two conclusions. Firstly, a geometry that has a high surface to volume ratio needed to be part of the solution. Furthermore, the air spaces resulting from this increased ratio needed to be connected to a sufficient extent so that the flow of oxygen can reach them. Secondly, that due to this resulting complexity, it needed to be materialized through digital fabrication tools.

5.2. Architectures of the fifth kingdom

Fungi are eukaryotes that are classified in their own kingdom – *the fifth kingdom* (Kendrick, 2017) characterized by their mode of nutrition through absorption. They have a tremendous variability in morphology,

Fig. 5. Bio Ex-Machina, Biological meets Digital Computing & Robotics. Source: © Officina Corpuscoli / Maurizio Montalti, 2019.

physiology, and ecological behavior (Bennett, 1998). Known for secreting a diverse array of enzymes, fungi can transform their surrounding environment through degradative enzymes, the synthesis of useful metabolites, or the production of Extracellular Polymeric Substances (EPS). Their metabolic processes can be harnessed through biotechnology for industrial applications.

Fungi have been long used in fermentation processes and food production. More recently, they have been employed for the production of bioactive compounds such as antibiotics, enzymes, and vitamins, as well as biofuels. An emerging area of interest is their role in environmental remediation, particularly in habitats compromised by industrial activity, mining, and agriculture (Money, 2016).

In recent years, there has been a growing interest in employing fungi for architectural, design, and packaging applications, often referred to as mycelium-based composites (MBC). Traditional approaches have mainly relied on casting these biocomposites into moulds. However, *Pulp Faction* diverges from this method by materializing through additive fabrication techniques, which have the potential to offer higher specificity in both the process and the resulting geometries.

While there are several projects like the early Mycotecture in 2009 (Mok, 2018), Hy-Fi Tower (Nagy et al., 2015), and MycoTree (Heisel et al., 2017) that have focused on fungal biocomposites for architectural applications, the scope of the project presented here was to utilize them through digital fabrication techniques. Previously, additive fabrication with living biocomposites has been primarily explored in the medical field for applications such as tissue engineering. However, these differ considerably in both scale and fabrication conditions from architectural applications.

At the time when *Pulp Faction* was conceived, the large-scale precedents in additive fabrication with mycelium biomaterials were very limited. Nevertheless, several projects that emerged around the time of *Pulp Faction* are noteworthy. Bio Ex-Machina (Fig. 5), a collaboration between Officina Corpuscoli and Co-de-iT (2019), focused on 3D printing with living mycelium to produce small-scale components. These experiments hint at the possibility of creating larger architectural elements such as walls through stacking and interlocking techniques. Tree Column by Blast Studio (Hahn, 2022) is another project that employed 3d printing to create a column using fungal biocomposite made from waste coffee cups. Unfortunately, details about their process remain undisclosed. Elsacker et al. (2021) employed a subtractive fabrication method using a block of casted fungal biocomposite. The digital fabrication was done while the material was alive, thereby allowing it to grow again post-manipulation and enhancing its performance. An experimental study by Ramsgaard Thomsen and Lim (2021) explored a hybrid 3d printing technique combining living fungal composite extrusion with the manual deposition of inorganic aggregate for support, showing high potential for geometrical variation if automated.

Pulp Faction extends the literature by employing additive fabrication techniques to work with fungal biocomposites on a larger scale. Our methodology thus fills a significant gap in the literature and establishes a foundation for future research in the rapidly evolving field of fungal biomaterials in architecture.

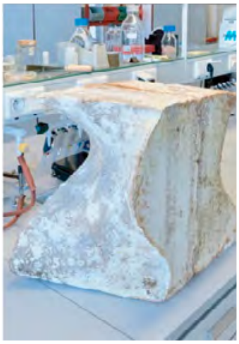


Fig. 6. Living self-healing mycelium components. Self-healing of two wire-cut mycelium-based elements. Source: Elsacker et al. (2021).

5.3. Methods

This project required an expanded methodological approach due to the involvement of living organisms. Unique to this project is the fact that its materialization took place in two different types of production spaces: the microbiology laboratory and the 3d printing workshop. Consequently, the development of the project required continuous navigation between the tools, methods, and protocols of both spaces.

The following describes the methods used for the design, fabrication, and growth of the final demonstrator of *Pulp Faction*, *Protomycokion*. This section provides an abbreviated description of the methods used for the design, fabrication, and growth of the final demonstrator of *Pulp Faction*, *Protomycokion*. A more in-depth description is presented in Goidea et al. (2020) and . Goidea et al. (2022).

5.3.1. Computational design

The design was done using pre-defined components and custom code in Grasshopper for Rhinoceros 3D. The main generative algorithm was based on a reaction-diffusion simulation, with its development over time plotted on the vertical axis. This was run inside a column geometry designed to increase surface area at the global scale. A third algorithm was employed on a component scale, meant to connect separated sections within each printed component, as well as provide additional lateral stabilization. The same algorithm was additionally optimized to generate a single, continuous toolpath, allowing for a faster and more stable fabrication by reducing defects commonly associated with liquid-fibrous deposition (Goidea et al., 2020).

5.3.2. Fungus

The fungus used was a Gloeophyllum sp., which is a brown rot (Goidea et al., 2020). It was obtained from the Microbial Ecology group, where all the experiments and microbiology protocols took place. The fungus was grown and propagated on agar plates with a malt-yeast medium. The fungus was kept at 20 °C. For the preparation of the pulp[6], a new plate was propagated, and incubated at 25 °C for seven days, until the mycelium has covered the entire surface of the plate. For the inoculation of the pulp, an entire agar plate was cut in 5 mm * 5 mm squares and placed on the fibrous substrate. Here, it was incubated at 25 °C for seven days. This ensured that the pulp contained a much higher number of fungal cells, which was beneficial in several ways. Firstly, the wider spread of the fungus reduced the chance that a contamination would take over the fabricated component. Secondly, after the pulp was mixed, the mycelium was broken into a high number of cells and hyphae fragments, which then each acted as a source from where new mycelium grew. This ensured a faster colonization and more uniform biotransformation of the final component.

5.3.3. Pulp

The substrate was prepared by mixing the following, with proportions representing the final recipe: sawdust (16.3% wt[7]), cellulose (5.4% wt), clay powder (16.3% wt), xanthan (2.6% wt), and water (59.4% wt) (Goidea et al., 2022). The sawdust was sourced from 8mm birch wood pellets, made by Scandbio.

To prepare the mixing of the sawdust, the wood pellets were soaked in water (20% of the total water) in order to separate the particles. The separated particles have then been filtered through a sieve with a mesh size of 2 mm, so as to pass through the extruder when 3d

[6] Pulp is a growth medium, or substrate that has been inoculated with fungus (Goidea et al., 2020).

[7] Total weight.

printed (Goidea et al., 2022). The cellulose fibers have been shipped in several compacted clumps that were difficult to separate mechanically, therefore they have also been soaked in water, and stirred to form a slurry. These additional steps for wood and cellulose particles have been taken in order to ensure a homogeneous substrate, as unevenly distributed lignocellulosic fibers can create clumps that not only can create material anisotropy, but risk clogging the extruder.

The substrate components were mixed until even with an industrial dough mixer. The substrate was then placed in 2L glass beakers, covered with aluminum foil, then autoclaved. This was done with a large volume autoclave run on the sterilization program at 126 °C and 15 psi for 20 minutes. After autoclaving, the substrate was left to cool down to room temperature and inoculated as explained above. After fungal inoculation and the first stage of growth (pulp pre-growth), the pulp was partially solidified: the fungus had begun redistributing nutrients throughout the beaker. This resulted in water seeping on the bottom of the beaker, and a denser mycelial network on the top of the pulp. Due to this behavior and in order to evenly spread the mycelium through the pulp, it was mixed again, with more xanthan gum added to complete the total 2.6% wt, as well as water. The pulp was continuously mixed on low speed until achieved a soft, homogeneous consistency.

Fig. 7. 3d printing with living pulp.

5.3.4. Printing

The pulp was 3d printed using bioFDM method (Goidea et al., 2022), in which the geometry is deposited in a layer-by-layer manner, similar to LDM, but where the fusing takes place through biological growth (Fig.7). The printing was done on a Vormvrij Lutum v4, with a print bed volume of 430 mm * 460 mm * 500 mm, suitable for bridging the scales from laboratory samples to architectural components. This 3d printer has originally been designed for additive manufacturing in clay, and therefore was suitable for this project as the pulp has a comparable consistency to wet clay. It operates through a combination of rotating auger and air pressure (Goidea et al., 2020), and this resulted in less clogging than previous attempts made with a self-designed and built extruder that relied only on pressure to drive the extrusion. An additional benefit of this type of extruder is that the stepper motor can be reversed, allowing for retractions, or a more immediate pausing of the extrusion, which is not possible to control to the same extent when working with air pressure only.

An extension of the printing setup was done through the addition of custom aluminum frames as new print-beds, that were also kept in place during the growth stage. These were fabricated from hexagonal expanded meshes fixed to aluminum frames, to allow the components to be transported without deformation. These have been made in four different sizes, grouping similar sized components of the column: 400 mm * 450 mm, 400 mm * 300 mm, 300 mm * 200 mm, and 150 mm * 150 mm. Each mesh has been sterilized with ethanol and placed on the printer and has acted as a new print-bed, with the component being fabricated on it. After printing, another mesh of the same size was placed on the top of the component, for post-print stabilization. Besides the lateral stabilization, the main purpose of the meshes was to allow air flow to and from the component during growth. This air flow was generated by the metabolism of the fungus, which needed oxygen to grow.

5.3.5. Post-printing

This fabrication step included the growth stage and the following desiccation. After the printing was completed and the top mesh was placed on top of the component, these were placed inside a plastic box with a lid that was previously sterilized with ethanol. The box was then placed in an incubation room, kept at 25 °C. Each component was kept in the incubation room to grow for 4 weeks. After this period, the components were taken out of the box and placed in a drier. The drying conditions were set at 60 °C with ventilation for 24 hours to terminate the fungus, ensuring that the growth did not continue. Without this step, the components would eventually turn into compost. After the water has evaporated, the components were rigid and thus removed from the mesh. Since the first layer was printed on a mesh and not a flat surface, the pulp was pushed through the mesh holes. Due to this, the components were slightly sanded down on the bottom to remove the extra height.

5.3.6. Assembly

Protomycokion column consists of 30 components that are each 63 mm high. These have been stacked vertically, and a layer of modified pulp was placed between the components. This was allowed to grow at room temperature conditions, binding them two by two.

5.3.7. Research by design

In order to arrive at the protocols for biofabrication, a methodological approach was needed to navigate a vast space of parameters, and combine several methods from different areas of expertise, as well as create new ones. The research by design methodology employed was particularly suited for this context as it allowed an iterative formulation of questions, analyses, continuous production of material, and engagement with scalar issues in a nonlinear manner. The need for bridging multiple requirements from different disciplines, without an established disciplinary route framed the issue as a wicked problem. Therefore, a methodology of exploration and reflection in the realm of design was well fitted to tackle this disciplinary multiplicity.

The non-linear dependencies were not only between areas of expertise, but also between scales. The continuous iteration of sub-questions, design proposals and materializations followed by analysis allowed the gradual growth of a body of knowledge regarding these interdependencies and their implementation, which incrementally increased the number of interconnections and scale of reach.

Fig. 8. Opposite page: Protomycokion.

The following will elaborate on the research by design methodology as described by Ramsgaard Thomsen and Tamke (2009), with regards to material evidence as a means of knowledge production and evaluation. The notion of “probe”, originally defined as a speculative design exercise, is used to lay out the design parameters and theorization (Ramsgaard Thomsen & Tamke, 2016). However, here it was mainly expanded in the material realm, probing material potentials in very limited scope tests, and importantly, not limited to exclusively design speculations, as it will be elaborated below.

One of such probes was focused on testing substrate compositions for extrusion. The initial tests have been manually extruded, to eliminate potential unknowns regarding technology parameters. This probe tested different compositions through adjustments to proportions and variations of thickeners, to find out whether the material was consistent, could be extruded through an opening of a few millimeters, and was stackable on layers. The scope of the probe was also to assess the extruded material after drying, to gauge how stable and strong it is. Further probes were conducted on a similar material testing of the substrate composition, with the same recipe established through the manual extrusion, but this time automated with a 3d printer.

As mentioned earlier, not all probes were strictly placed in the realm of design. Several probes were placed in a more standard scientific experimental set-up. Here however, in the general research by design methodology they are contextualized as probes, as they are narrow tests, materialized, and furthermore contribute to advancing the design iterations. One such probe was testing whether the newly isolated fungus grows on the substrate that has been identified as extrudable, as well as on other similar lignocellulosic and cellulosic media. More details on the setup of this experiment can be seen in the visual journal.

After a series of probes that have fixed some base parameters, a set of prototypes was developed. These mainly investigated the technology for fabrication in combination with a living organism and introduced a designed geometry. Three species were chosen to be assessed for how competitive, and therefore compatible they were with the fabrication technology. The prototypes have then been evaluated through several methods. Firstly, whether the fungi successfully grew on the printed samples. Secondly, several tests were made to evaluate the

mechanical performance, the behavior of the printed material towards water vapor, as well as when submerged in water. These results are published in Goidea et al. (2020). One additional result of the evaluation of these first prototypes was that the differential growth algorithm used to generate the geometry was not suitable. It was chosen as it increased surface area, and while it was successful at this, it had no crossover which resulted in sections that were hanging from narrow connections, and therefore prone to be broken away. Secondly, the distance between extrusions was too small, as the walls merged into each other at points, eliminating the intended gap.

Through the evaluation of the prototypes, the best performing fungal species was selected, and clearer specifications for the geometry were formulated. All the initial findings were then integrated into a full-scale architectural fabrication experiment, aiming to produce the demonstrator. Its purpose was to test not just the scaling up of the size, with its associated structural challenges, but also the scalability of the biofabrication protocols and the laboratory protocols. Further issues of structural stability, assembly, and potential cumulative errors have been brought to attention through full scale production in a way that smaller tests would have not been able to. And lastly, another role of the demonstrator was to communicate the potential of the technology and the vision of its architectural application to a wider audience, as described by Ramsgaard Thomsen and Tamke (2016).

It is important to note that although the research inquiry has been described through the increasing levels of resolution in probe, prototype, demonstrator, this has not been a linear process. New probes have been made after the prototypes, after which new prototypes were produced again. Each evaluation has brought a new change to the protocol, and these have been incorporated into the next generation of material investigations, minimizing errors, while at the same time, through the exploratory nature of the investigation and the expansion into new and unknown territories, they have also brought about new kinds of challenges.

5.4. Visual journal

The following section is a visual journal describing the journey that led to the fabrication of *Protomycokion*. It shows the series of experiments, mainly done in the microbiology laboratory. Its aim is to tell the story that took place behind the scenes, all the work and the love that has gone into the project. It is not an exhaustive presentation of all the experiments that were set up, but it presents processes that support the overall method, and that thus have not been published as explicit methodological parts. Nevertheless, they do reveal a more complete perspective of how these different approaches, methods, and scales have been navigated. Through the journal you are invited backstage, to take part of the process development, the materially driven research by design method, and the constant interfacing with scales.

Pulp Faction was started by an encounter with a fungal comb. These are naturally occuring structures that are remarkably complex. Besides pointing to a new way of relating to materiality and production, these structures seemed to show properties that are relevant to architectural application. The intrigue to find out whether we can fabricate them at architectural scales, and what are their affordances here has been the driver of the following design experiments.

Our journey to fabricate these fungal composites led us to Namibia. Here we opened termite mounds in search for Termitomyces, the fungi that constitute half of the symbiosis in the fungal combs. Although we hadn't realised it at the time, this was a long shot. Isolating fungal species from the wild for the first time without the guidance of a microbiologist didn't have a high chance of success. To this was added the challenge of a lack of a laboratory, so we couldn't sample from the open combs in a sterile environment. This needed to happen in the open savanah, and with all its particles flooding in and contaminating the inside of the clean mound when we opened it. We have decided on an isolating strategy focusing on collecting fungal nodules from the fungal combs. These are self contained small spheres of a few millimeters filled with fungal spores, that grow out of the comb structures.

These two fungal comb samples are taken from the same mound, with the same species and growth conditions. What is different between them is their age.

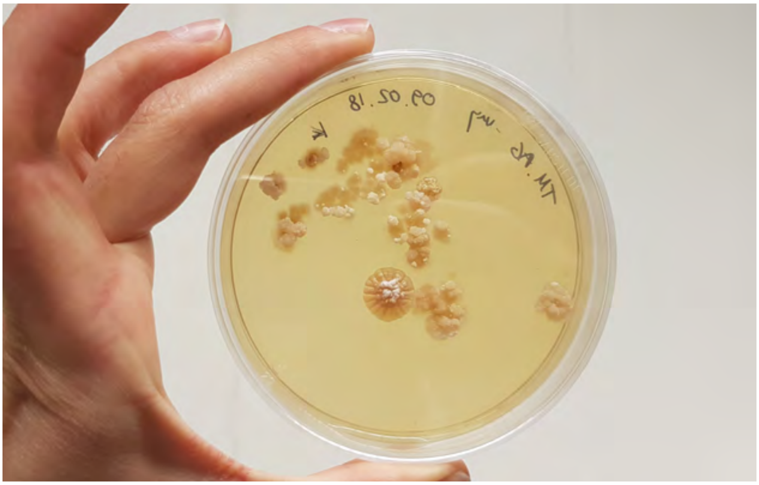
The top comb is a young specimen, with the dark colors showing oxidized plant matter. It is also possible that the darker shades are lignin. The specimen is relatively soft and easily to break. The individual depositions laid out by the termites are visible as close to spherical clusters, and they are weakly bound to each other.

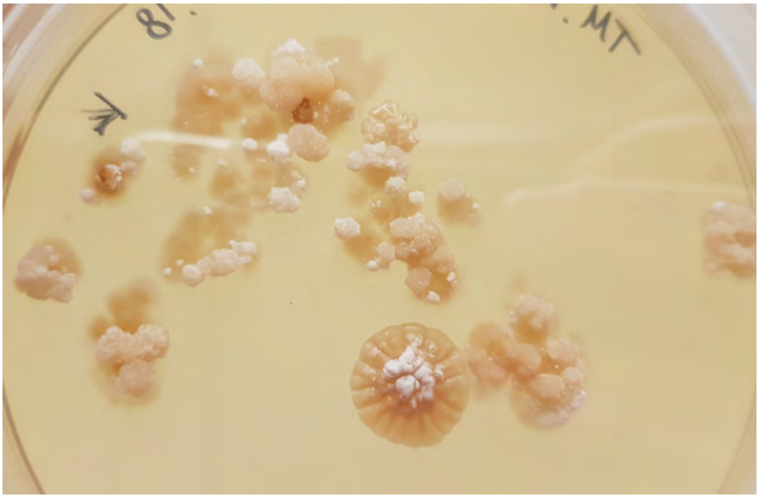
The bottom comb is an old specimen. It is more elastic, but still frail and easy to break apart. Most other samples that we have observed and collected have an age in between these two, medium brown color, and were significantly more strong.

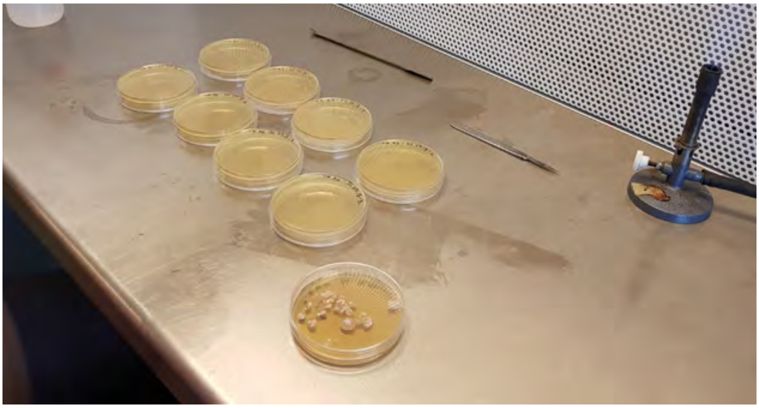
The selected mound and the collection preparation took place at the Omatjene Research Station in Otjiwarongo.
These are some of the samples collected from the mound. The white nodules are visible on several samples.

As we didn’t have typical laboratory facilities, we had to improvise. We prepared these by filling each with 0.75 ml water and boiling them together to sterilize them. Then on site we had sterilized tools with a burner, and picked nodules one by one and placed them in the flasks. From this trip we returned with a bag of more than 30 flasks with fungal nodules to be incubated. Each flask was then emptied in the lab on a agar plate with growth medium, resulting in 32 inoculated petri dishes. The plating took place 6 days after the collection of nodules.

This is the library of microbial species that grew from the collected nodules. These were incubated at 20 degrees Celsius for 19 days after plating. Some plates didn’t exhibit much growth, while others showed several species of filamentous fungi, bacteria, yeasts, and others have multiple species growing on the same plate. We had expected that the lack of ideal conditions during isolation had opened up access for contaminations to take over some nodules. However, it was still highly surprising and exciting to see all the wide variation of species slowly revealing themselves, from an invisible scalar realm to a rainbow of morphologies visible to the naked eye. The left section shows the plates under natural light, while the right section presents the plates against the light.

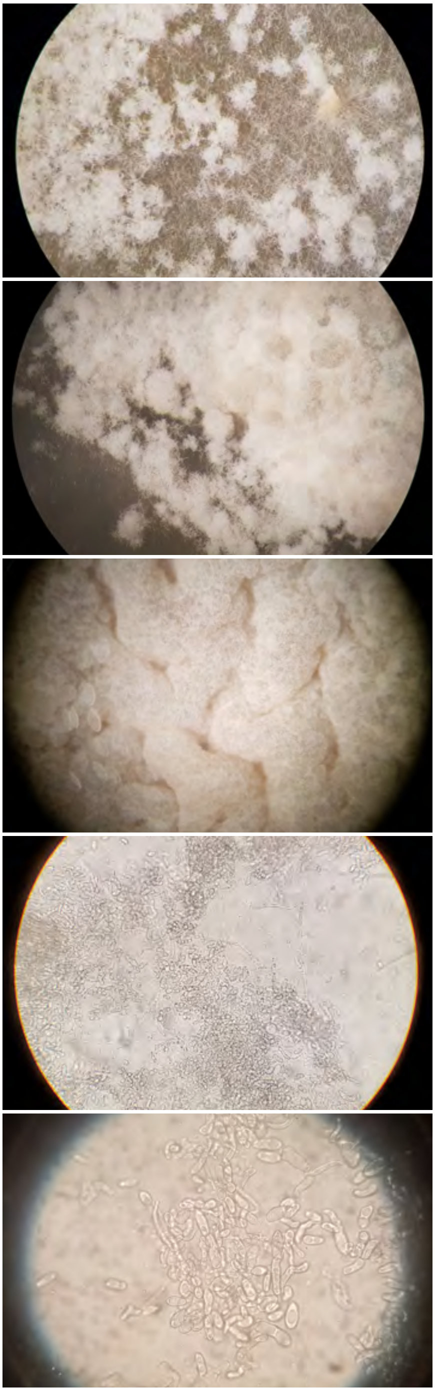


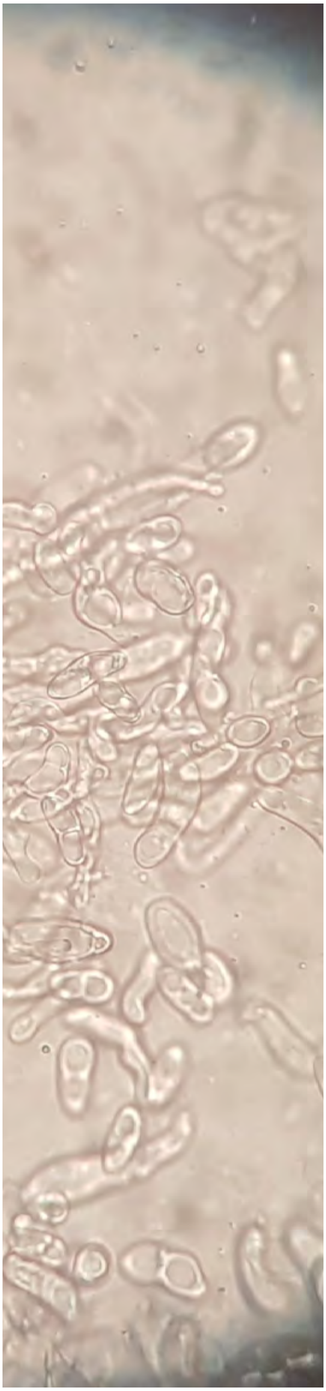




Luckily, plate #13 had the coveted fungus growing - the only one in the library. We now had a strain of Termitomyces michaelseni, which I further propagated onto 8 plates, to isolate it from other species that grew next to it.

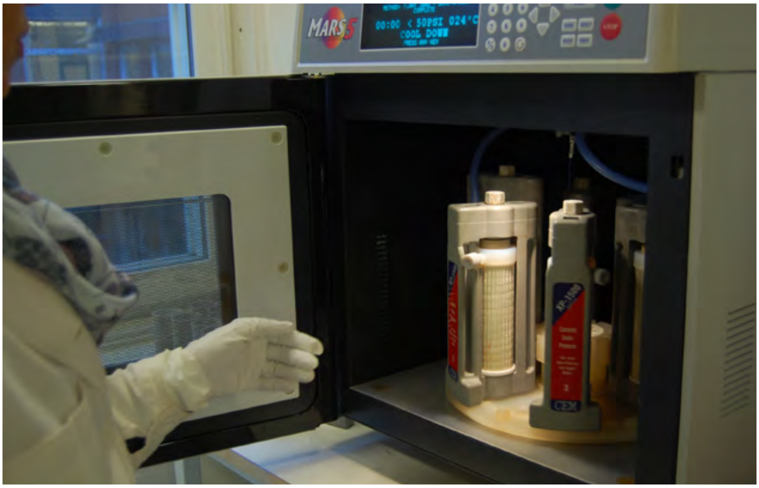
From different regions of the plate #13 I made replicates on 8 new petri plates. The images show the growth on day 5 after re-inoculation (left), on day 29 (middle), and on day 64 (right). The vertical columns show samples 1-8. These have all been successful propagations of the fungus. This particular Termitomyces fugus is from now referred to as TM.AG.

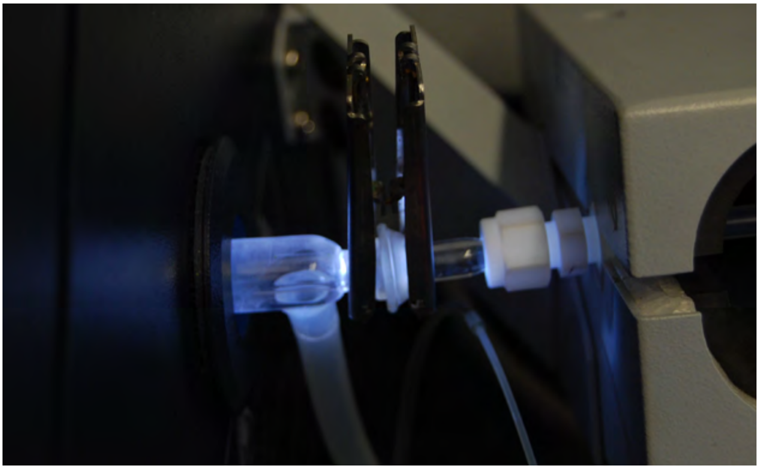




After having successfully isolated the strain, we wanted to understand the growth morphology of Termitomyces, so we have observed it under the dissecting microscope. The magnifications are, top to bottom: 5x, 10x, 40x, 100x, 400x. The scalar jumps reveal very different morphologies at each level. These range from specks, to highly folded mats, and connected cells. It is interesting that Termitomyces does not grow forming long mycelia, which then would grow into mats or skins, but instead its cells remain rather segregated.

Before attempting to create a fungal-lignocellulosic composite, we wanted to have an insight into the chemical composition of the biological precedent. This meant delving into the molecular scale.
We wanted to find out what is it that makes the comb hold together, and give it its properties. This was done through an elemental analysis and carbon / nitrogen ratio analysis.
The sample 0 was taken from the bottom of the comb, sample 1 from the middle of the comb, and sample 2 from the top.





ICP-OES testing (Inductively Coupled Plasma Optical Spectrometry). Fungal comb samples were dissolved and introduced as an aerosol into a plasma torch. This torch, using argon gas, produces a plasma that ionizes the sample elements. This ICP technique measured the emitted wavelengths. The ions and atoms emit electromagnetic radiation as they are excited. This wavelength is characteristic of each element in the periodic table. By detecting the wavelengths, the elements can be identified (Houck, 2009).
This method is useful for detecting trace elements in samples.

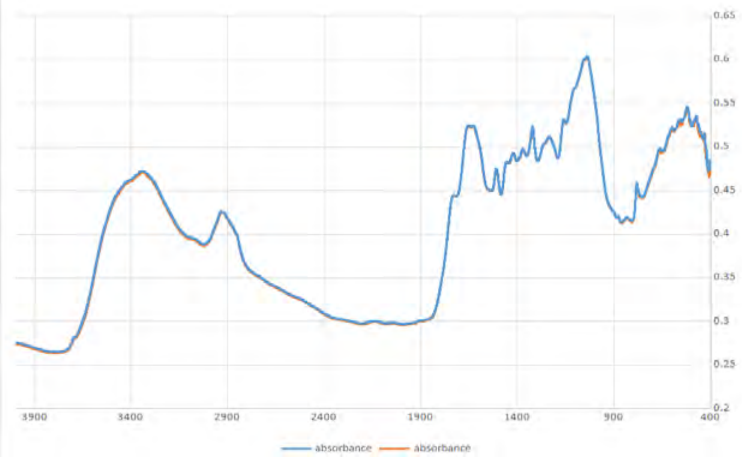
We calculated the C/N ratio and estimated the amount of basic elements with important roles for cellular growth such as Fe, Mg, and P. We also saw that there was variation in the composition of the samples. For example sample 2 is poor in N and also much poorer in other elements such as Mg and P. This interesting, as it shows the progression of the fungal comb as it is deposited and grows.

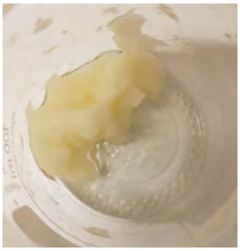
	Fe 238.204	Mg 285.213	P 213.617
0 CN:	1.39	1.62	0.62
1 CN:	3.02	2.29	0.53
2 CN:	1.67	1.58	0.41

	TC	TN	C/N Ratio
0 ICP:	428	16	27
1 ICP:	395	14	27
2 ICP:	410	12	36

IR (infrared) reflection data in the region 400-3900 cm^{-1} showing peaks that suggest the presence of lignocellulosic material.

Fe, Mg and P were analyzed using ICP-OES, Optima 8300 from Perkin Elmer and TC/TN were analyzed with Vario Max CN from Elementar.





A. cellulose
0.55g

B. wood
0.55g

C. cellulose + wood
0.3g 0.3g

D. cellulose + wood + starch
0.3g 0.3g 0.05g

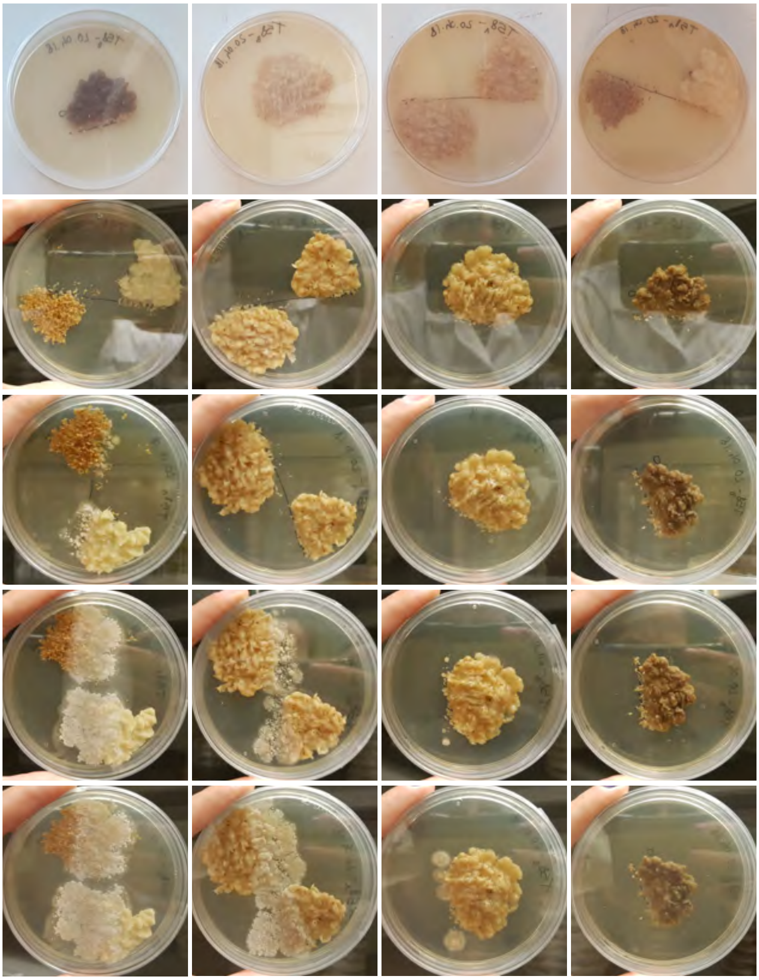
E. cellulose + wood + xanthan
0.3g 0.3g 0.05g

F. gypsum paper
0.55g

A series of experiments followed, aimed at understanding the growth parameters of Termitomyces. From our knowledge, there had been no previous research on growing Termitomyces on other media than liquid or agar culture medium. In this experiment, different types of wood fibers were tested for growth: cellulose, wood, wood in combination with cellulose, as well as two different thickening agents: starch and xanthan gum. Additionally, recycled paper from gypsum panels was tested to see how biocompatible it is compared to the other fibers.

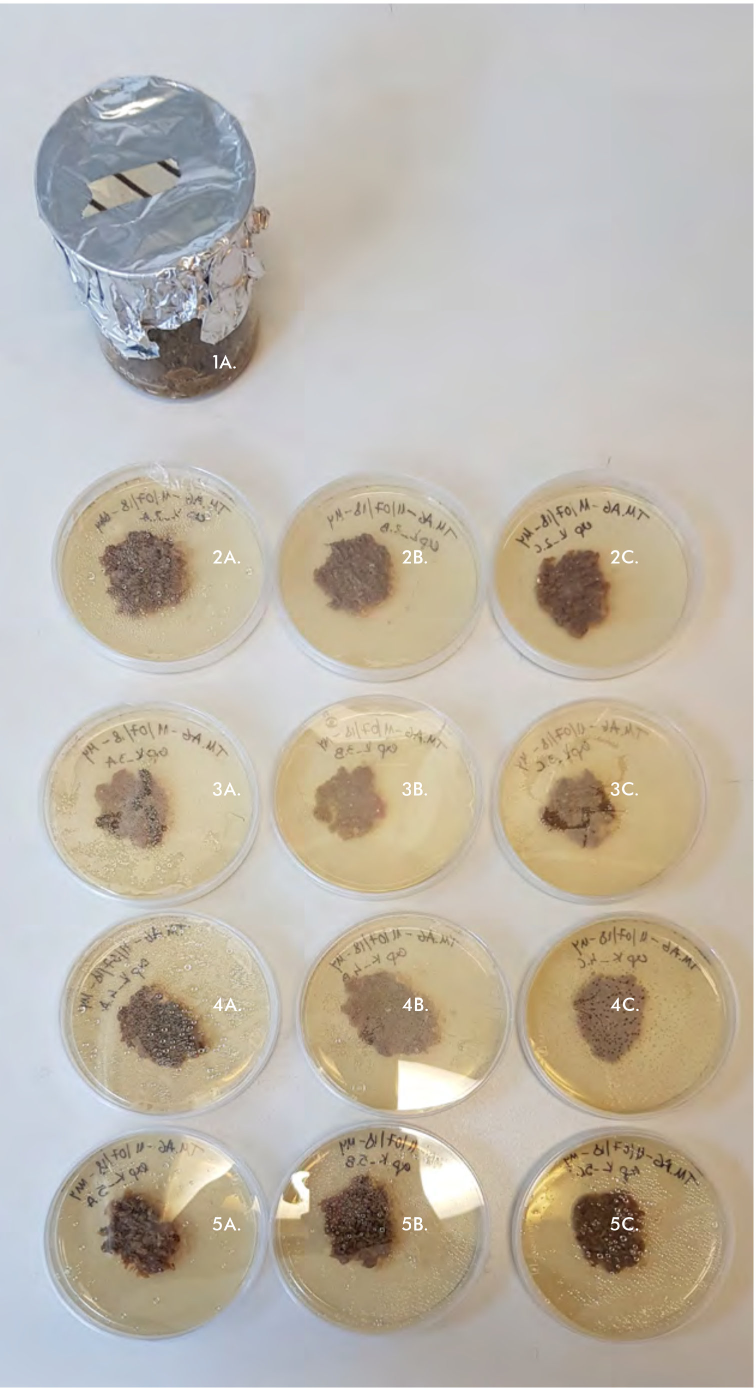
Top row dishes were plated with the following, left to right: gypsum paper, cellulose + wood + xanthan gum, cellulose + wood / cellulose + wood + starch, wood / cellulose.

The plates show, in the vertical rows, the growth levels of TM.AG on each fiber composition, on the following days, starting with day 0 (inoculation day): day 6, day 14, day 28, day 35, day 53.



TM.AG has been compared to TN.T58 (pictured on this page), a species of Termitomyces natalensis received from a collaboration with the Laboratory of Genetics at the University of Wageningen. The results of this experiments show the following: 1. TM.AG grows a lot faster than TN.T58, probably because it is a more recently isolated strain, although other factors could be at play as well. 2. Generally, the fungi grew on all mediums, except gypsum paper for TN.T58 which showed no growth. 3. Gypsum paper was the best medium for growth for TM.AG, with rapid development and even growth.

TM.AG growth on E. wood, cellulose and xanthan gum (top), and F. gypsum paper. The difference in growth patterns is visible here, the gypsum paper being colonized with a more even spread, while the mix is more localized.



Since the gypsum wool was the most successful sample, we have decided to do a more extensive experiment focusing on this fiber source, and then testing other parameters, such as inoculation temperature, the addition of other fibers sources, such as sawdust, raw cellulose, and xanthan gum.

Based on Pulp 5* - with Primewool as cellulose source

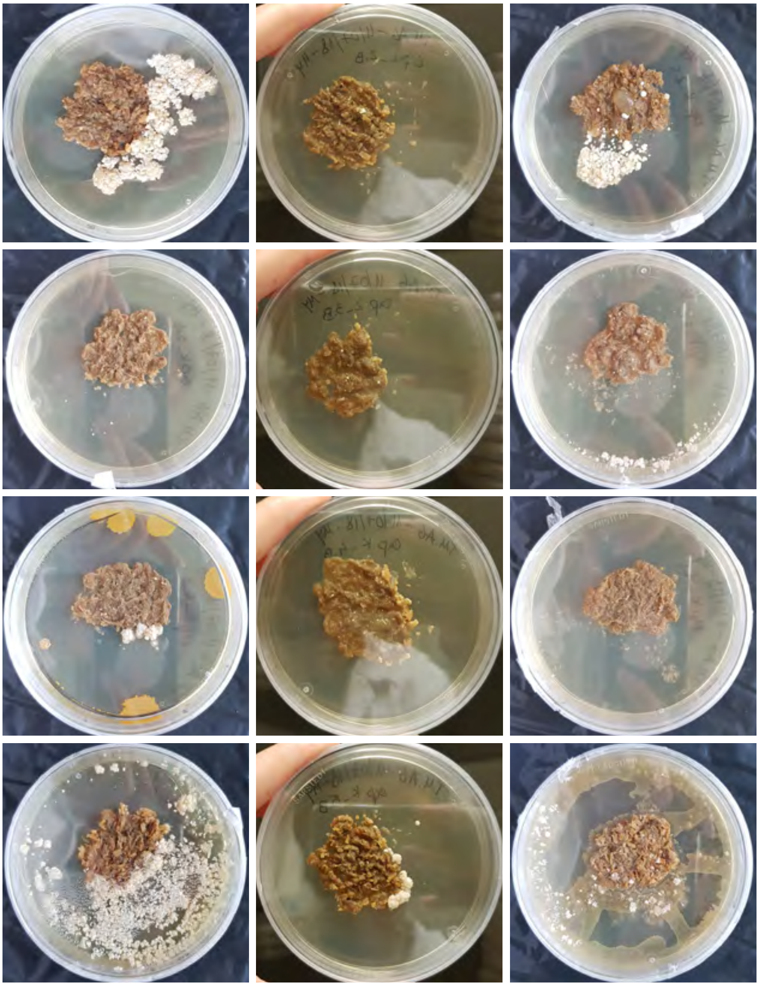
1. Beaker with Pulp5* + TM.AG
    - _3g Primewool
    - _3g wood (coarse)
    - _37.5g water
    - _0.2g xanthan
        - A. LS TM.AG @ 35° C

2. Petri dish with Pulp5* + TM.AG
    - _0.5g Primewool
    - _0.5g wood
    - _6.2g water
    - _xanthan
        - A. dry inoculation @ 35° C
        - B. dry inoculation @ 25° C
        - C. LS @ 35° C

3. Petri dish with PW only + TM.AG
    - _0.5g Primewool
    - _6.2g water
        - A. dry inoculation @ 35° C
        - B. dry inoculation @ 25° C
        - C. LS @ 35° C

4. Petri dish with Primewool + xanthan + TM.AG
    - _0.5g Primewool
    - _6.2g water
    - _xanthan
        - A. dry inoculation @ 35° C
        - B. dry inoculation @ 25° C
        - C. LS @ 35° C

5. Petri dish with Primewool + xanthan + TM.AG
    - _0.5g Primewool
    - _0.5g wood
    - _6.2g water
    - _xanthan
        - A. dry inoculation @ 35° C
        - B. dry inoculation @ 25° C
        - C. LS @ 35° C



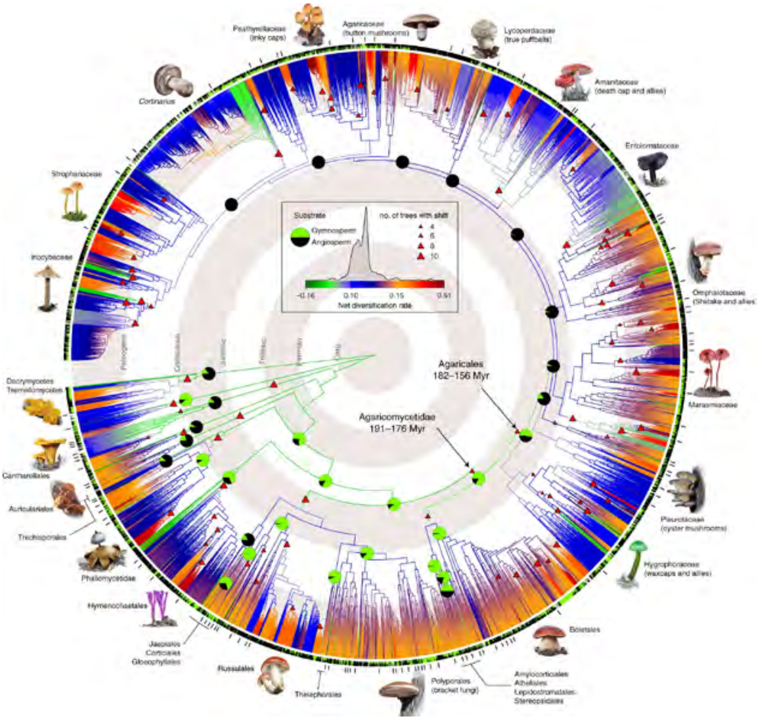
The first vertical column shows 2-5A, the second the 2-5B, and the third 2-5C. None of the plates has shown growth on the fibers.

There has been small growth on plates 2A., 4A., 5A., K.2C., 3C., 5B., but only at the periphery of the pulp and/or the plates, so most likely running on the agar medium as sustenance. There is some contamination on plates 4A. and 5C., both from the high temperature incubator. We have concluded that the batch of gypsum paper used for all the setup in experiment K was different that the one used for experiment M4., which grew excellently. The batch used for experiment K then likely congtained fungicide, unlike the batch in experiment M4.

Although recycled fibers have a high potential in the field of biofabrication, it is important to have the full cycle information on the materials, to ensure biocompatibility.

Due to practical constrains, we have chosen to limit this exploration to three species, in addition to Termitomyces.
These images show the three species' fruiting bodies, popularly known as mushrooms. These have very clear differences in morphology. But perhaps more importantly, they each have different decomposition strategies. Byssomerulius (Bys.FD.578) is a white rot, Leucopaxillus (Leu.437.85) is a litter decomposer, and Gloeophyllum (Glo.1627) is a brown rot.

Left: Byssomerulius corium. Smithson, L., (2020). Netted Crust (Byssomerulius corium) [Photograph]. iNaturalist. https://www.inaturalist.org/photos/69477370 (CC BY-SA-4.0)
Middle: Leucopaxillus. Hollinger, J., (2010). Leucopaxillus albissimus [Photograph]. Flickr. https://www.flickr.com/photos/7147684@N03/4496737529/ (CC BY 2.0)
Right: Gloeophyllum. Monster, H. (2015). Gloeophyllum trabeum [Photograph]. Panoramio. http://www.panoramio.com/photo/115495234 (CC BY 3.0)



Our assumption was that the best species for the fabrication of fungal composites is the one found in biological model, Termitomyces. However, the three other fungal species were added in order to compare the growth rate, contamination susceptibility, and resulting material properties, in order to verify whether this is indeed the case.

The journey of working with fungal biomaterials then took us on the vast scalar realm of fungal variation, opening up an immense spectrum of possibilities in biofabrication: with an approximation of 2-4 million species of fungi available (Hawksworth & Lücking, 2017), each with their own biochemical and morphological capacities.

Varga, T., Krizsán, K., Földi, C., Dima, B., Sánchez-García, M., Sánchez-Ramírez, S., Szöllősi, G. J., Szarkándi, J. G., Papp, V., Albert, L., Andreopoulos, W., Angelini, C., Antonín, V., Barry, K. W., Bougher, N. L., Buchanan, P., ... Nagy, L. G. (2019). Megaphylogeny resolves global patterns of mushroom evolution. Nature Ecology & Evolution, 3(4). https://doi.org/10.1038/s41559-019-0834-1 (CC BY 4.0)

The results of the previous experiment have not concluded before I set up another experiment. Here, different temperature conditions and different sources of Termitomyces have been inoculated. However, as the recycled cellulose has been from the same source as in the previous experiment, the result has been the same unfortunately: no growth in any of the beakers.

Each beaker:
_3g recycled cellulose fibers
_3g wood
_37.5g water
_0.2g xanthan

L1. 2 x beakers with Pulp5* + TM.AG
A. @ 30° C
B. @ 25° C

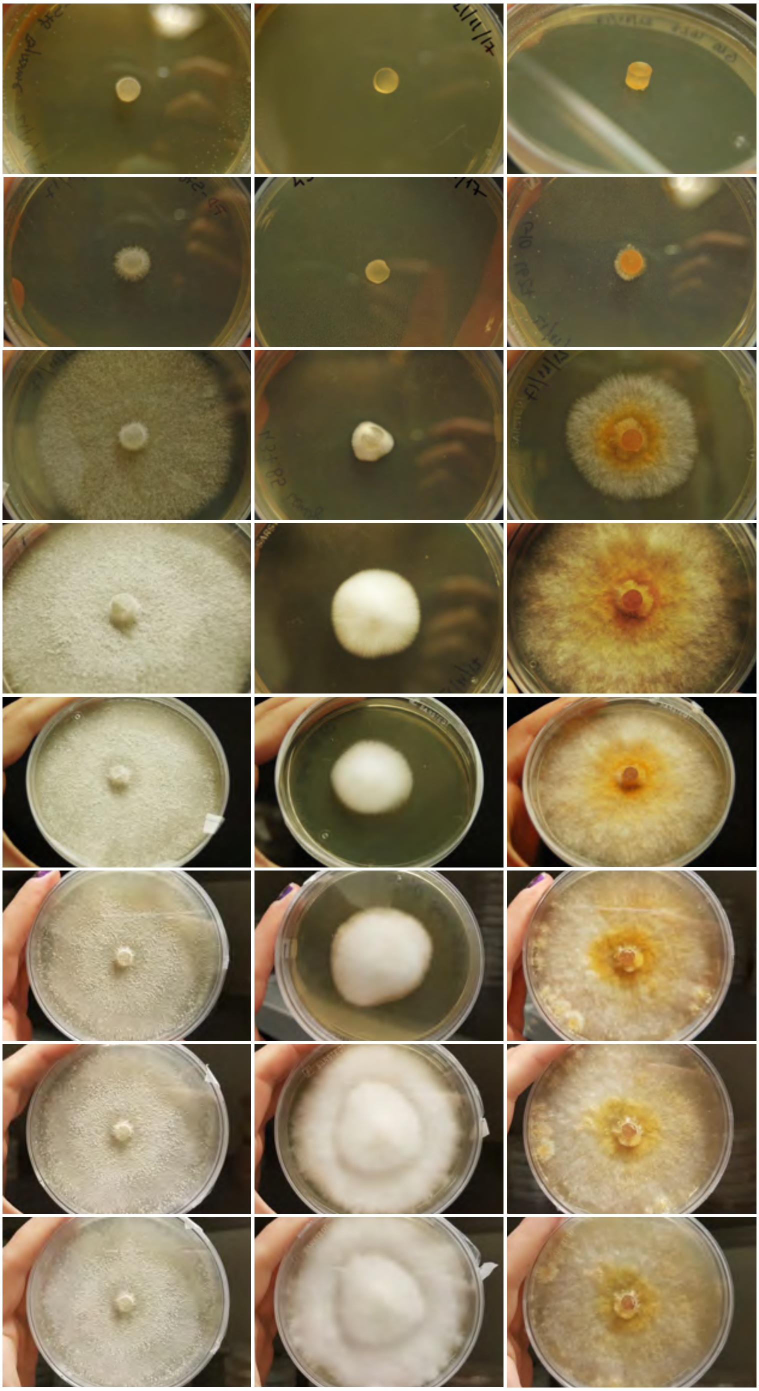
L2. 2 x beakers with Pulp5* + TM.AG from experiment M4.
A. @ 30° C
B. @ 25° C

L3. 2 x beakers with Pulp5* from experiment N1. + TM.AG from experiment O.A.
A. @ 30° C
B. @ 25° C

L4. 2 x beakers with Pulp5* from experiment N1. + TM.AG from experiment O.B.
A. @ 30° C
B. @ 25° C

L5. 2 x beakers with Pulp5* + Glo.1627
A. @ 30° C
B. @ 20° C

L6. 2 x beakers with Pulp5* + Bys.FD.578
A. @ 30° C
B. @ 20° C



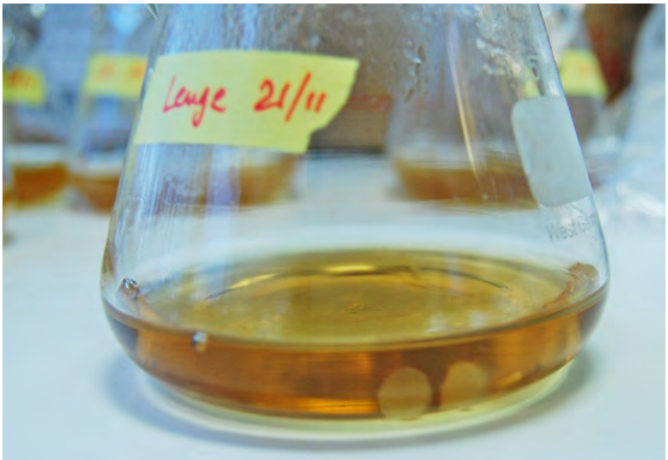
The left column shows Byssomerulius, the middle Leucopaxillus, and the right one is Gloeophyllum. Not only their fruiting bodies are different, but on a petri dish it becomes visible that their mycelium has a different growth morphology and distribution as well.

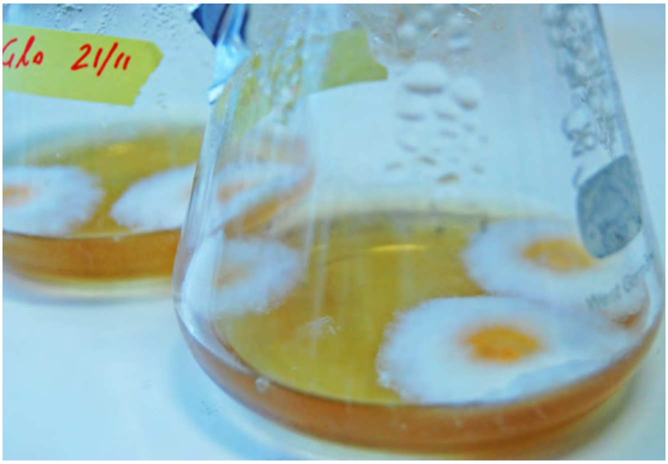
The photos are a series of photographs taken of the same three petri dishes over time. The the photos are taken after 1, 2, 7, 14, 20, 29, 62, and 79 days of growth. These show that Leucopaxillus is growing much slower than the other two species. Byssomerulius is slightly faster than Gloeophillum, with visible growth after only one day.

We also tested the propagation of the fungal strains in a liquid medium.

This method had the advantage of an easier inoculation of the pulp, as it only required the contents of the flask to be poured over the substrate.

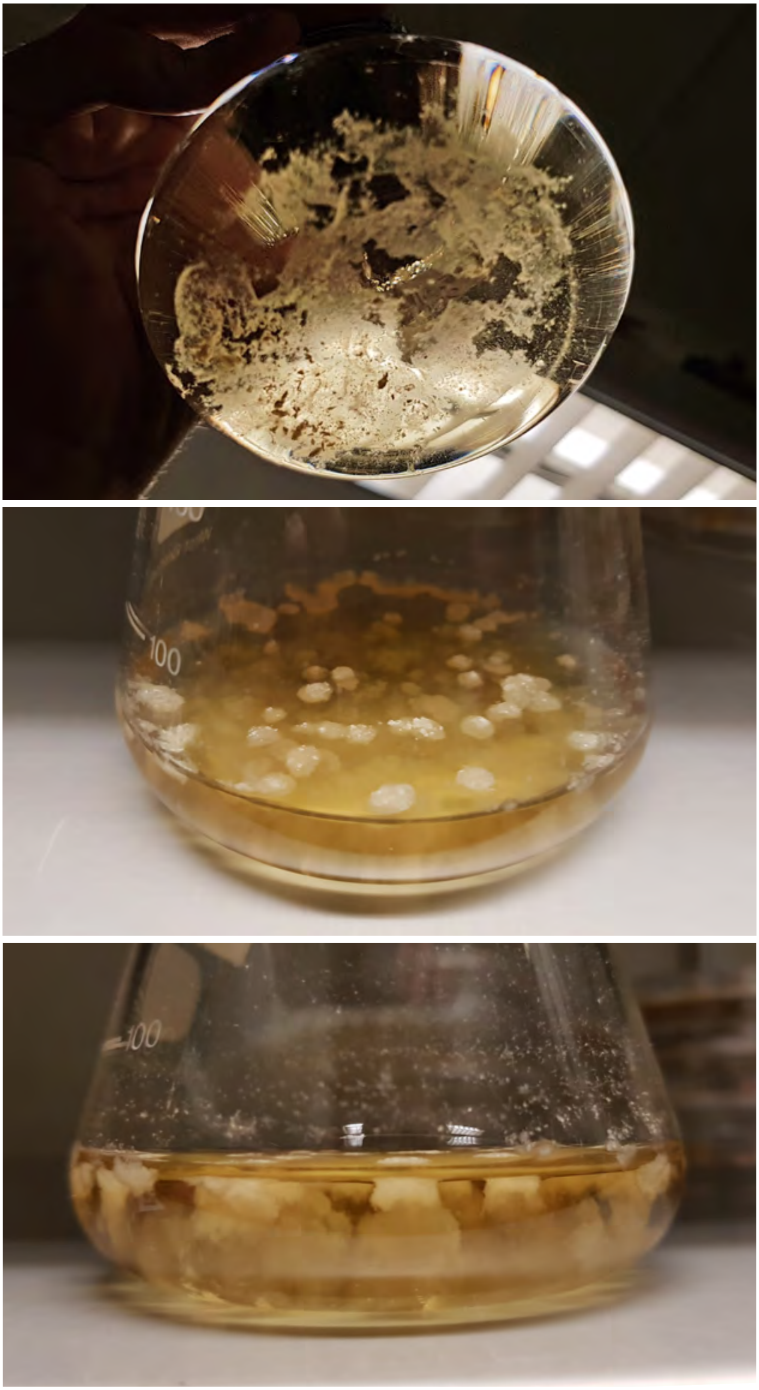
However, after 7 days of growth at 25 °C, the results were mixed. Bys. FD.578 has developed a translucent mycelium that has spread widely in the flask, reaching 30 mm in diameter. Leu.437.85 had instead barely any visible growth: this strain seemed to not prefer liquid mediums. And finally, Glo.1627 developed visible growth after only 1 day. In day 7, it showed thick white mycelium that reached 20 mm in diameter. The mycelium formed a thick skin that was difficult to break apart when mixing in the pulp at the inoculation stage.

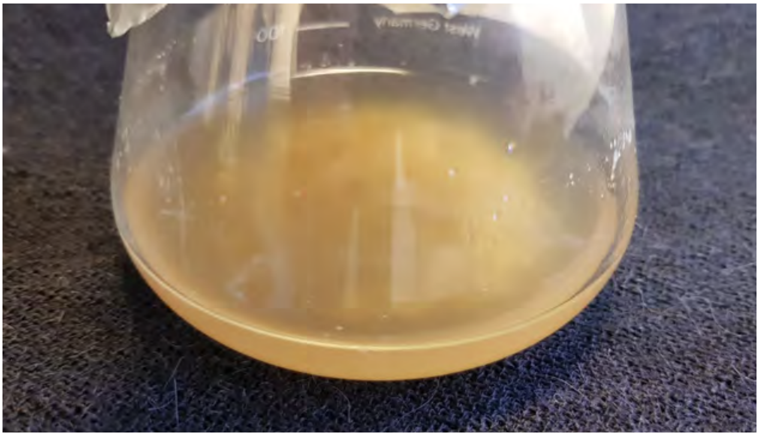




We did the same test for liquid growth with TM.AG. However, here we have also tested to compare the growth with a spinning incubator. The hypothesis has been that shaking introduces more oxygen in the liquid, as well as breaks apart cells so that there are more growing points, which would result in a higher mycelial mass.

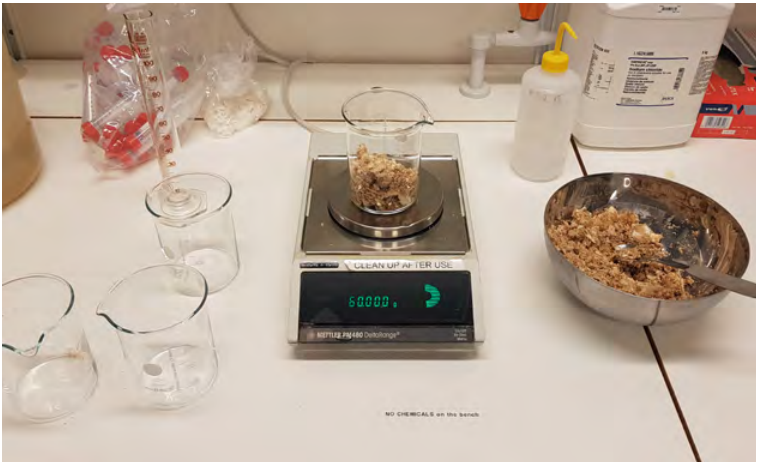
After 5 days of incubation in the static liquid medium there is a similar level of growth compared to the spinning incubator. The mycelium has grown as a thin film on the surface of the liquid.
However, after 27 days, there is excellent growth in the flasks. There are insular patches on the surface, but the growth goes down to the the bottom of the flask.



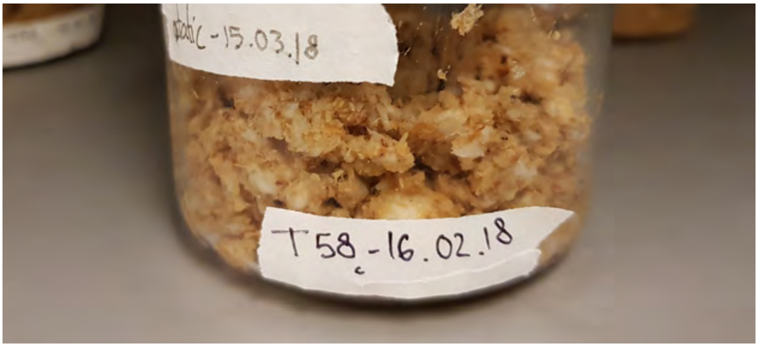


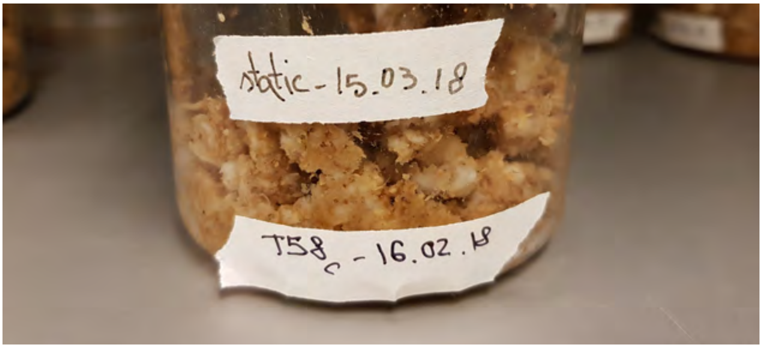
First image shows the growth after 5 days in the spinning incubator. It can be observed that the mycelia have grown into small coiled structures and one very long coil.
After 27 days, as shown in the bottom two images, there is more growth but it is not as rich as we expected. The liquid has turned slightly opaque, potentially filled with separated cells.

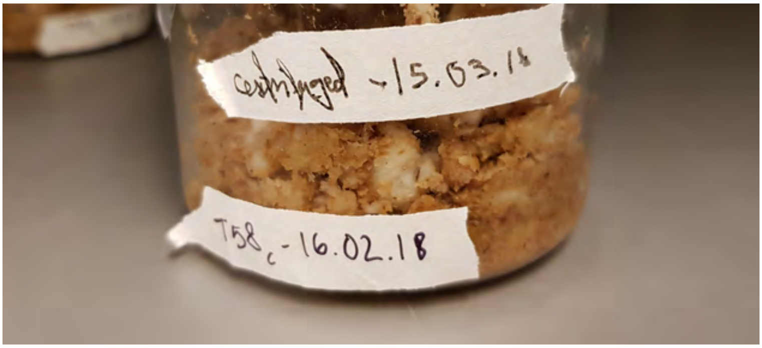
The cellulose and sawdust were mixed in small batches to test the growth in laboratory conditions. The initial mixing method didn't include the separation of the cellulose clumps, and therefore resulted in an uneven spread of the cellulose, with larger fiber aggregates in the substrate.



The beakers show the growth after 55 days of incubation. There is not much visible growth.







Due to the lack of growth in the previous experiment which used liquid inoculum, we have set up a new experiment, where inoculation was done on pulp from solid agar medium instead.

Out of the 4 test beakers, only one showed TM.AG growth. This shows that the fungus is more difficult to work with, and has a low successful growth rate.

The middle image shows the growth after 41 days, although there has been visible growth after 4 weeks.

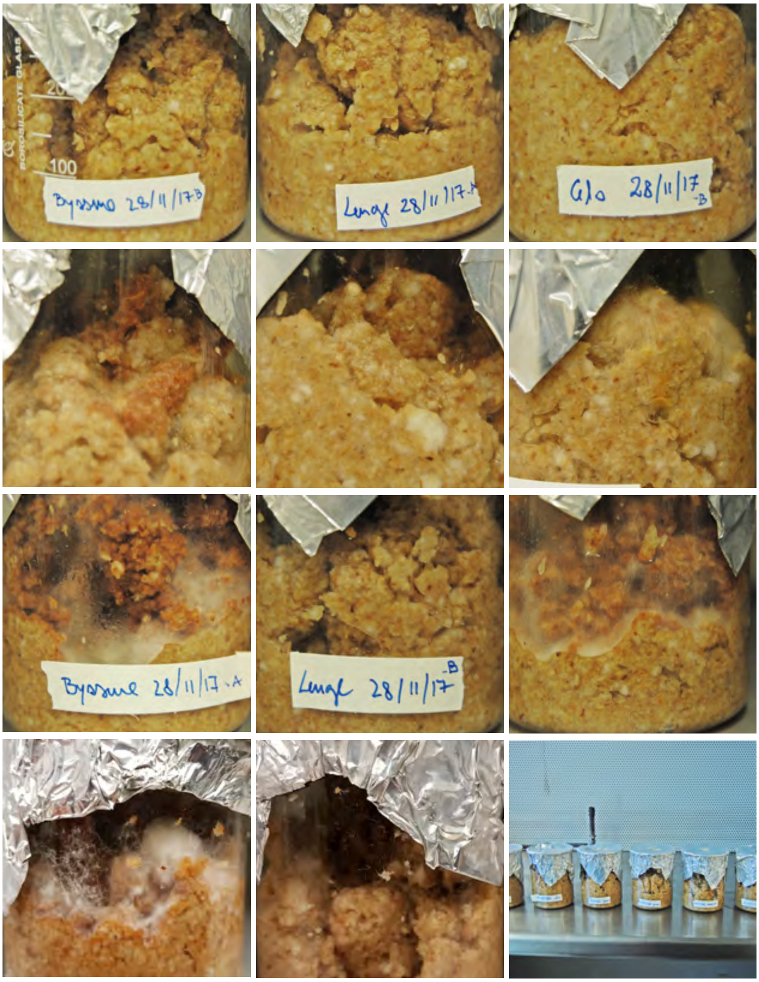
The bottom image shows the growth in the same beaker after 113 days. At this point it had become clear that Termitomyces it is an extremely slow growing fungus, and thus not likely a good option for biofabrication.

Here we set up another experiment, to test the growth of Bys. FD.578, Leu.437.85 and Glo.1627 on our substrate.

The substrate protocol was updated with the separation of cellulose clumps, so that the new version was more homogenous.

The inoculation was done through pouring the liquid medium on the substrate. Then it was mixed thoroughy, in order to break the mycelium to have a more even distribution, as well as have more starting points from where the mycelium would develop.

The photos were taken on the day of the inoculation, on day 7, day 13 and day 22. Bys and Glo have grown well, however Leu has not grown at all. This was probably due to the fact that the liwuid inoculum had minimal growth. However, the fact that this is a litter decomposer possibly made it struggle on the lignocellulosic medium. Because of these reasons, as well as the fact that it was growing very slow, we decided to not carry out further experimentation with Leucopaxillus.



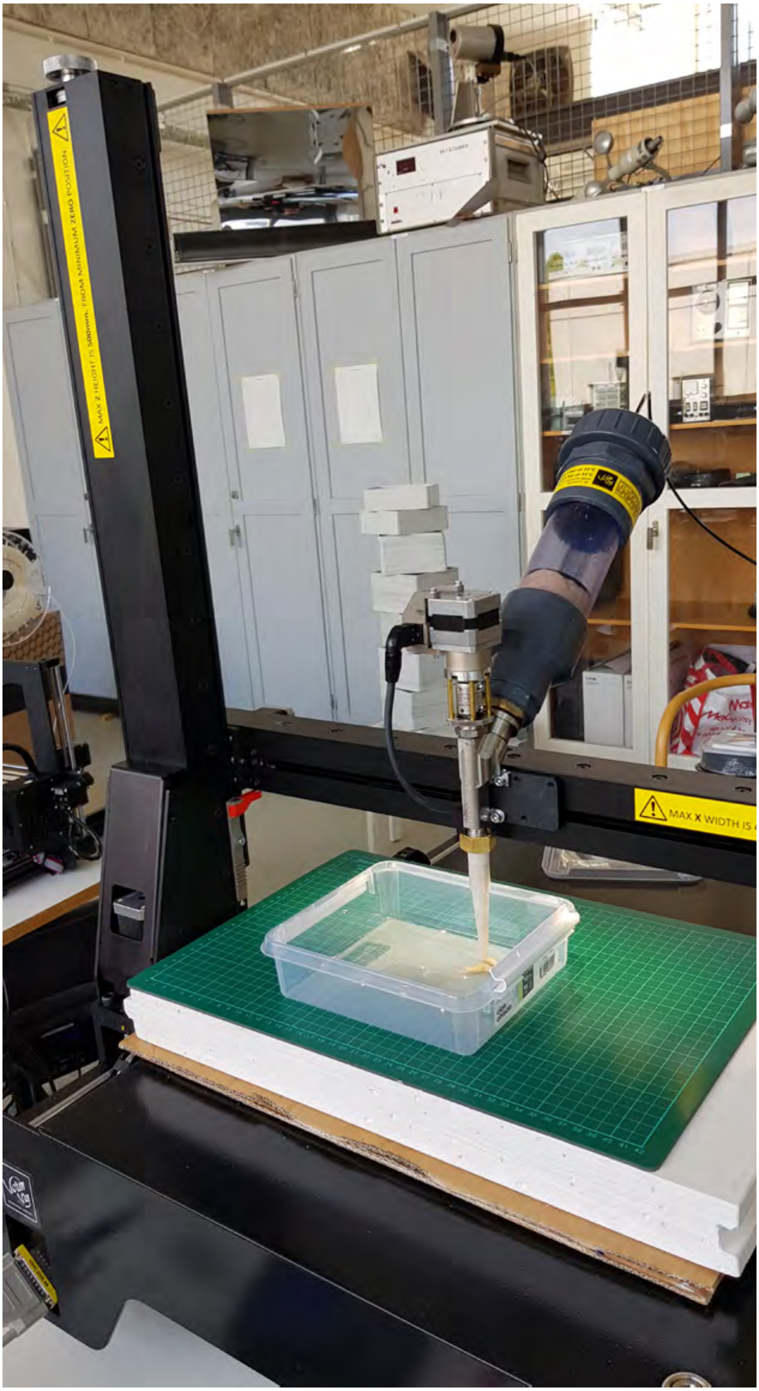
The next experiment gathered all the findings from the previous tests, and what was found as optimum parameters regarding inoculation method, growth conditions, and pulp composition.

Here, I set up 6 beakers, of 3 species with 2 replicates each. The right column represents the growth after 7 days from inoculation. All beakers showed successful growth, and therefore were taken into the next step of the experiment: 3d printing.

Our strategy was to try to do the protocols as sterile as possible, until reaching successful results. Then increasing the exposure to potential contaminants step by step by reducing the sterility of the techniques and moving towards architectural production methods.

Therefore, at this stage the beakers were mixed and loaded into the sterilized 3d printing cartridges inside the laminar flow cabinet, to reduce the risk of contamination.

Here is the walk through the park between the ecology building and the architecture building, with the loaded cartridge ready for 3d printing.



The printing however, was not done in sterile conditions, as this was not possible due to the size of the 3d printer. Therefore, I printed in the workshop in the architecture building.
The printing was done directly inside a sterilized box that also hosted the growth stage.
Testing the printing in conditions lacking complete sterility is something partly desired, since we wanted realistic conditions. The aim is not to have complete sterility in biofabrication at industrial scales for architectural applications.

The printing of TM.AG has proceeded well. However, there was a print fault at the end of the last layer, due to insufficient pulp inside the cartridge.

However, the experiment had confirmed extrudability of the living pulp with the current preparation protocols. The other question the experiment needed to answer was whether the fungus can grow in these conditions.

The other species have been also mixed, and to prevent the printing mistake that took place due to insufficient extrusion material, two beakers were mixed into one cartridge.

The last two species printed successfully, and one more sample was printed with only the substrate, to have as a control.
All three samples were placed in the incubator, and left to grow for 5 weeks.

The growth of Byssomerulius after 21 days.

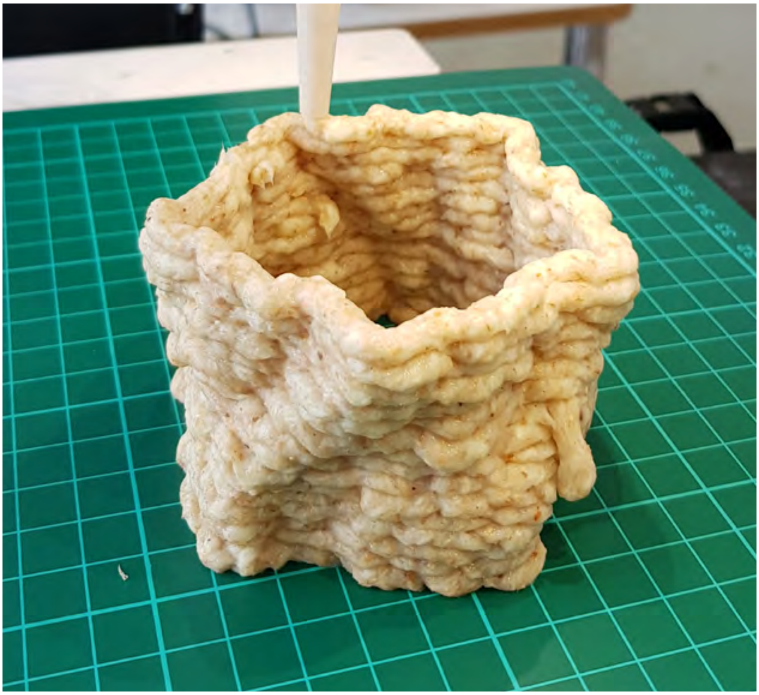
The TM.AG print test became contaminated. This is likely due to the fact that it is very slow to grow, so any other contaminants have a higher chance to develop. Additionally, it is probably not a very competitive species, as the environment inside the termite mound is highly controlled.

These are the successful printed samples of Byssomerulius on the top, Gloeophyllum on the bottom, and the control in the middle, after they were dried out. These did not get contaminated, and have shown even growth. Glo has shrunk the most during growth and dessication, probably as it had decomposed the material the most.

The substrate with the cellulose from recycled gypsum boards has been very easy to mix, as it came as loose fibers and not compacted. This shows the consistency of the substrate before loading into the cartridge.

The top image shows the printing process with the recycled cellulose. The image below is the print after it dried out. Since this sample did not contain fungus, it was left to air dry at room temperature. Some small parts have collapsed due to the cantilevering geometry.

This shows the pulp consistency before it was loaded into the cartridge.

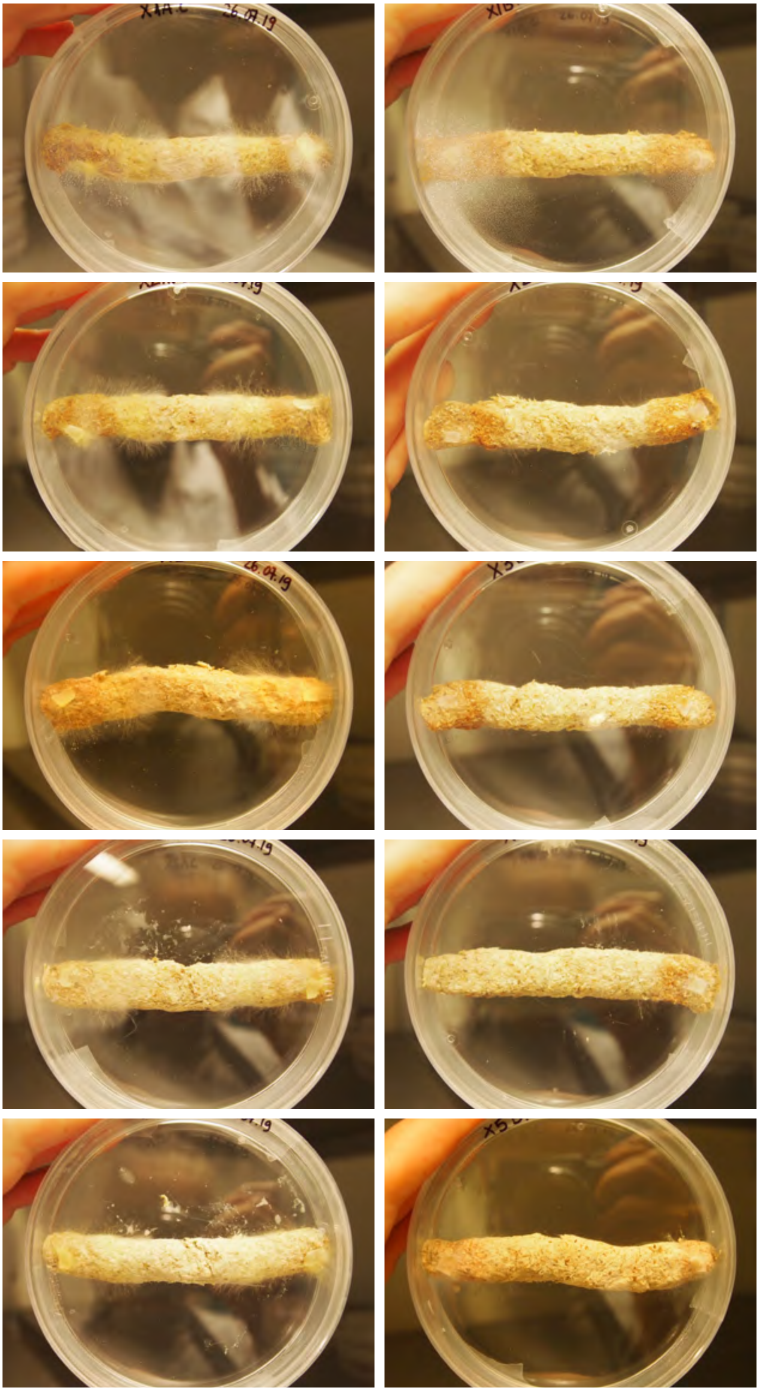


The top image was taken during the first prints with the substrate.
the bottom image is the same print after it dried at room temperature.
It is visible that the geometry has sagged a little bit, especially in the areas with overhangs, but overall it maintained the geometry reasonably, compared to the recycled fibers.
Recycling cellulose shortens the fibers, so we speculate that even though the printing material is very soft and unstable, the longer fibers in the non-recycled cellulose act as an internal reinforcement, keeping the geometry together.

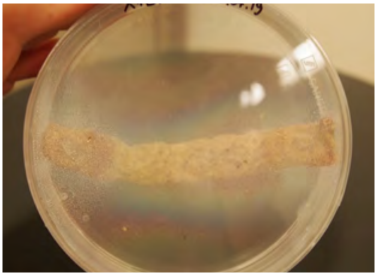
In this experiment we wanted to determine if the addition of clay to the substrate has an inhibiting effect on the fungal growth.

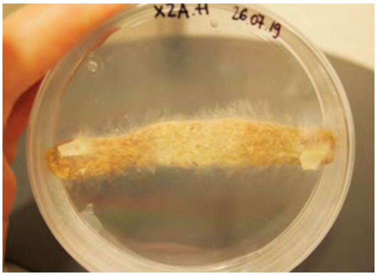
We set up 5 variables, with 2 replicates, and two temperature conditions: top rows have no clay, and the amount of clay increases progressively until the bottom rows, which have 60% clay.

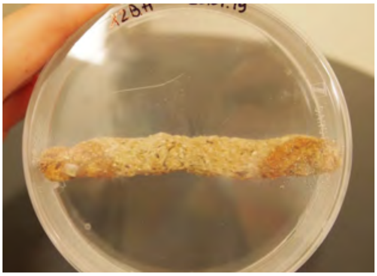
These two pages show the growth after 7 days of growth.

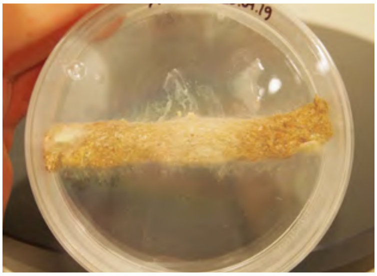


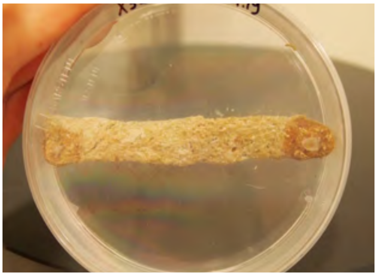
Here the same setup was incubated at 25°C.

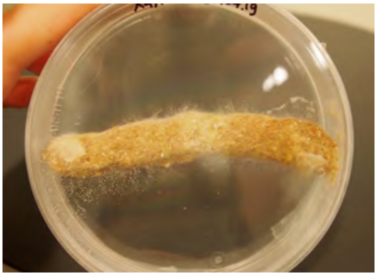


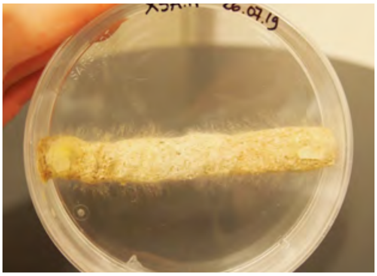


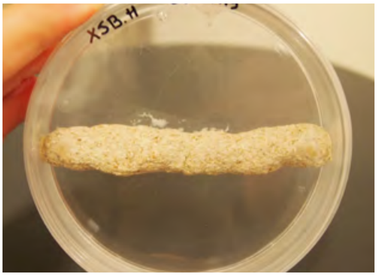


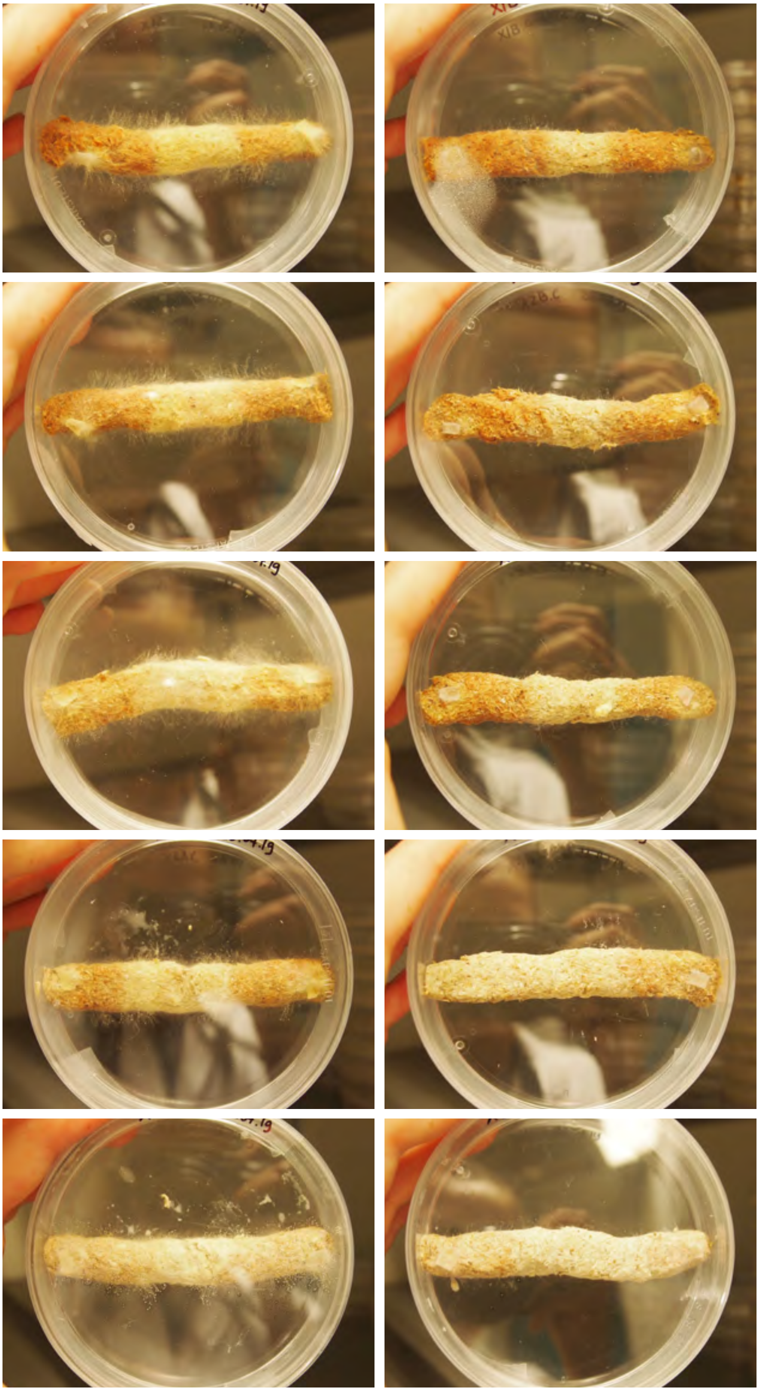




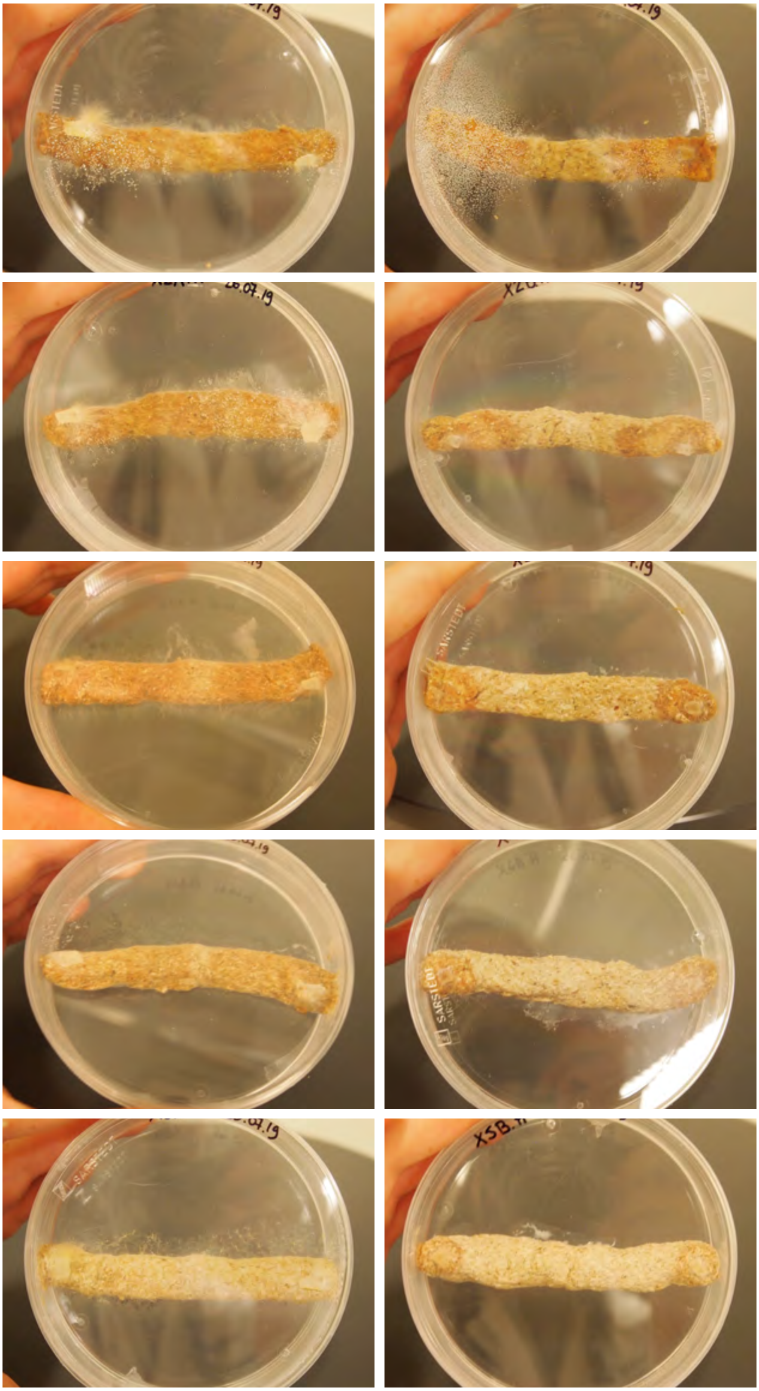






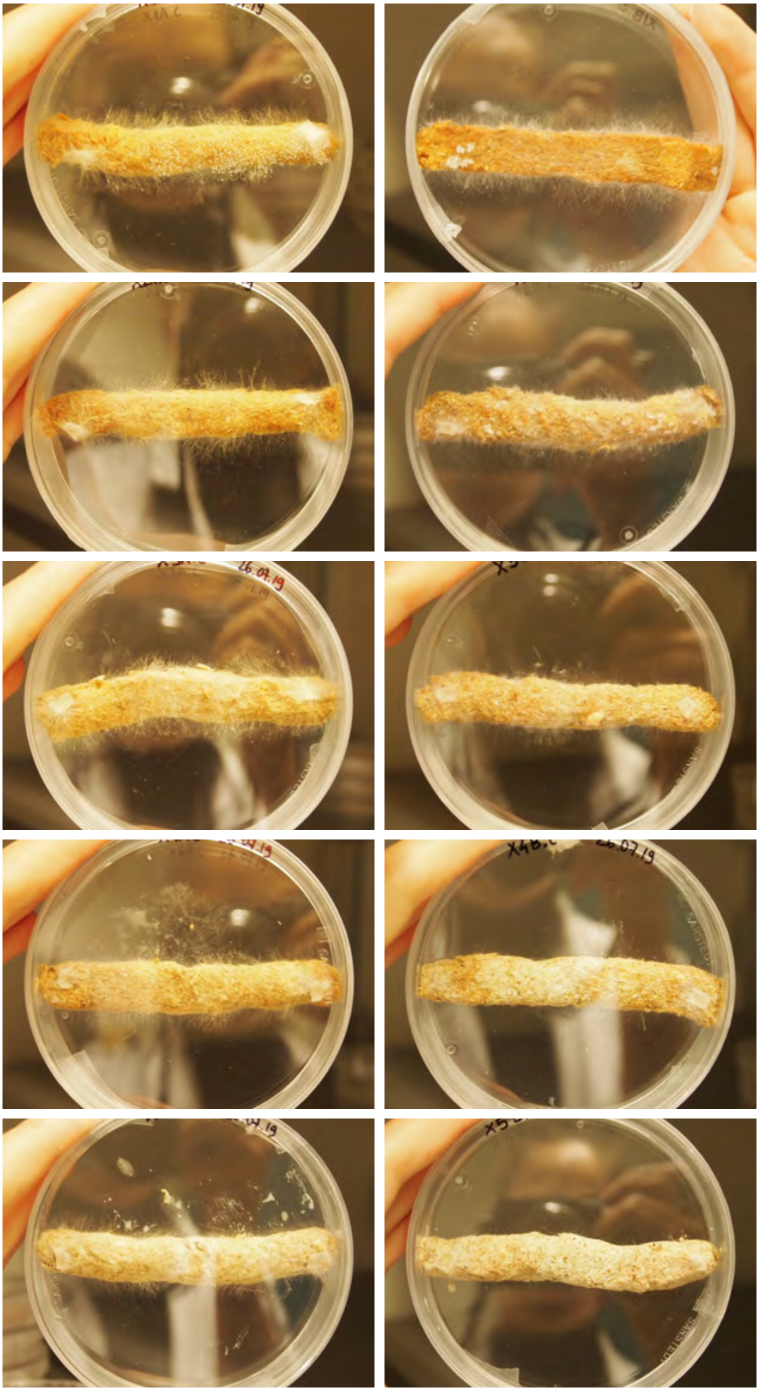


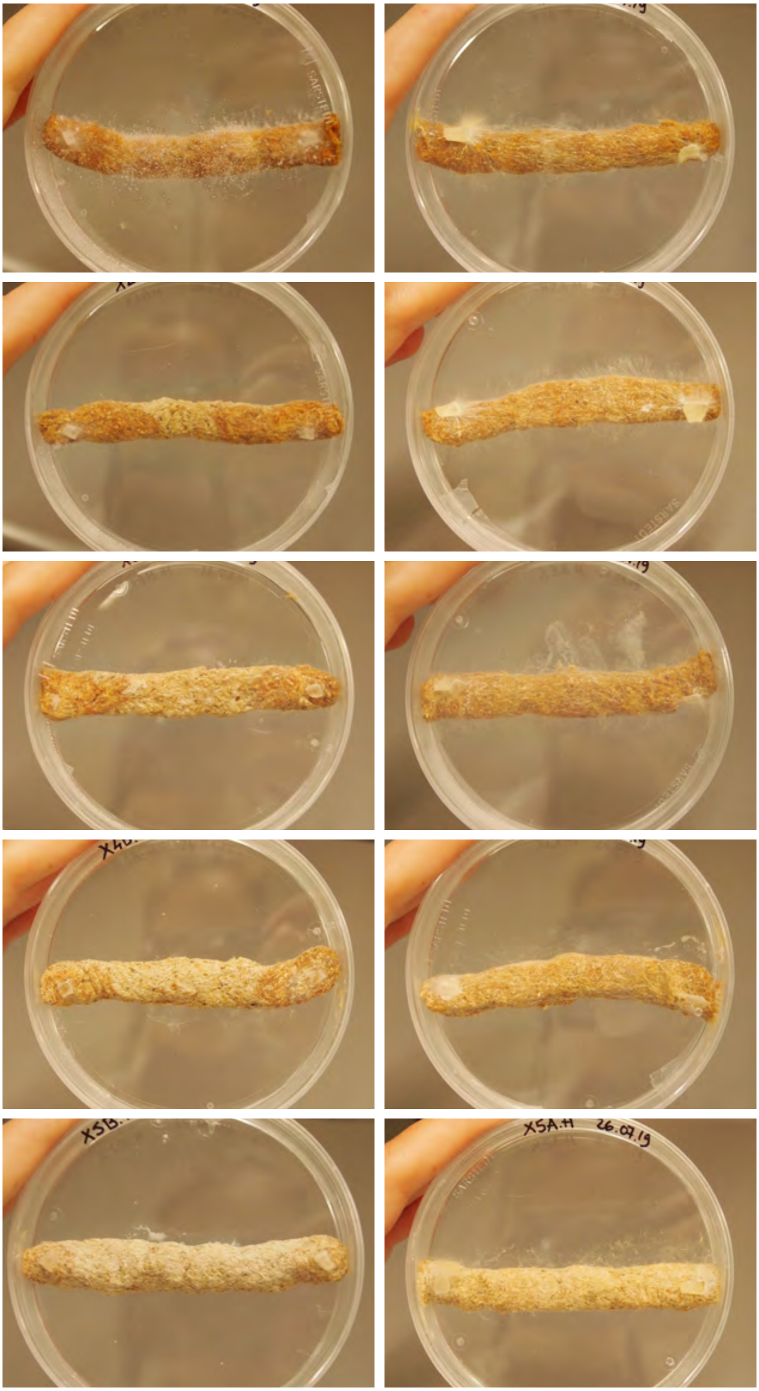
Room temperature conditions. These show the growth after 11 days from inoculation.



Plates incubated at 25°C, after 11 days of growth.

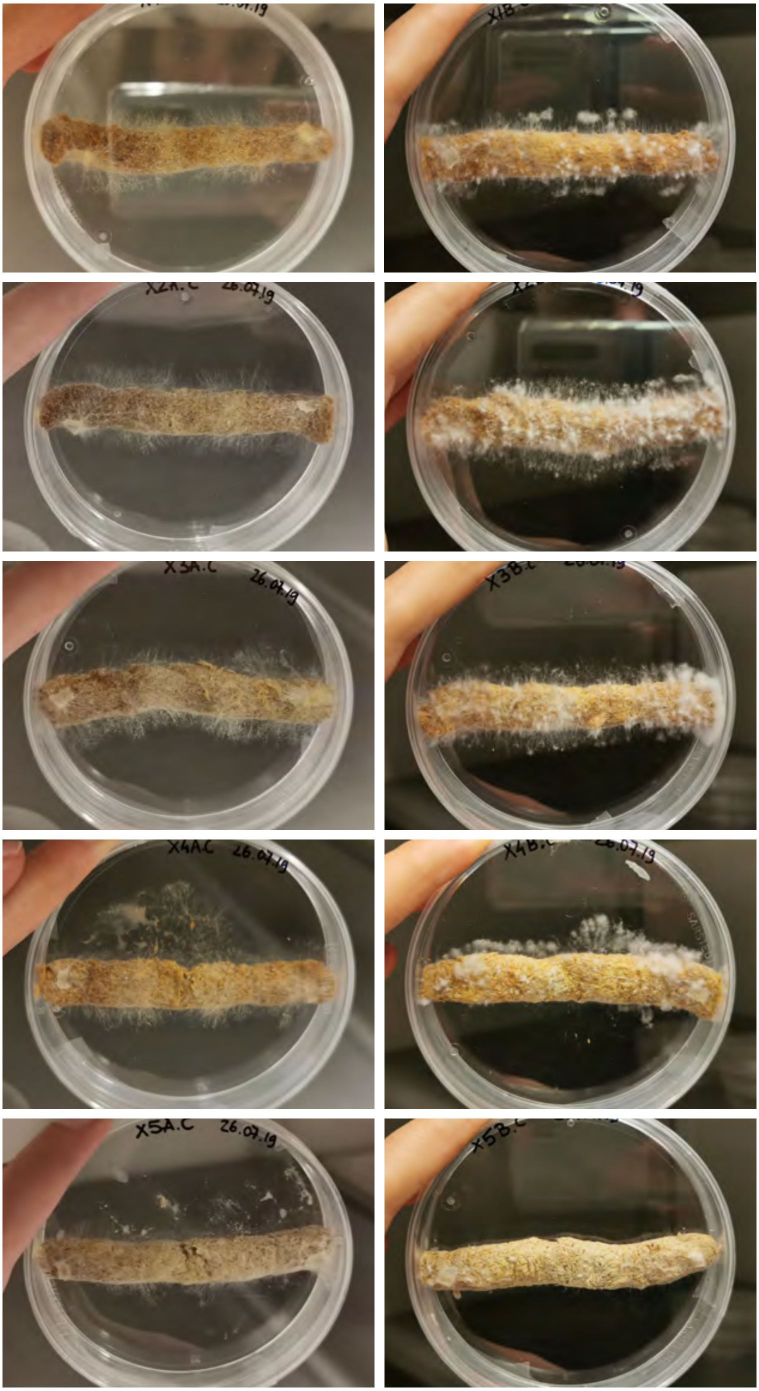
Room temperature conditions, after 20 days of growth.
These show that there was good fungal growth in the first dishes from the top. Although there still was growth even at high percentages, it was reduced and seemed weaker.
Although the ideal condition from the fungal requirements perspective is still without any added clay, the considerable benefits resulting from adding clay to the substrate have led us to decide on a substrate mix that include a small percentage of clay.

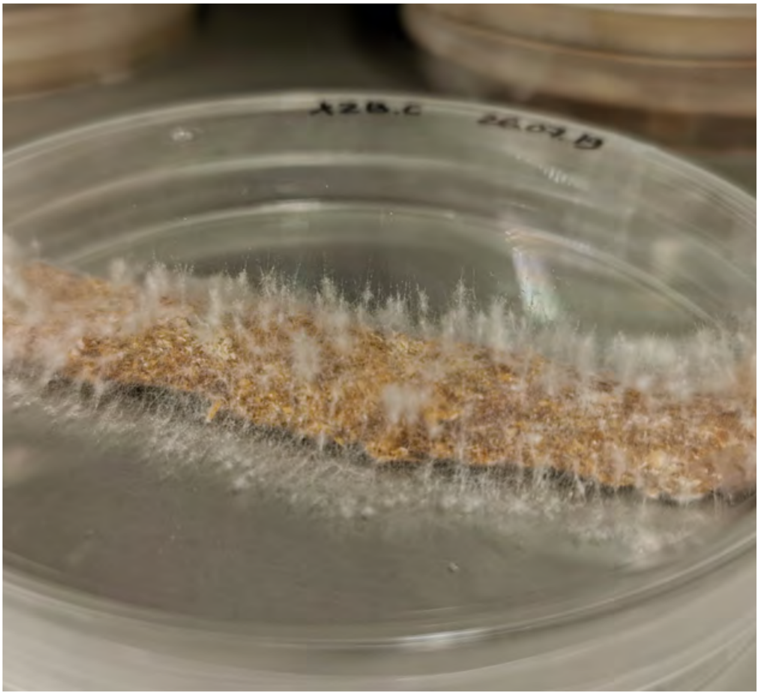


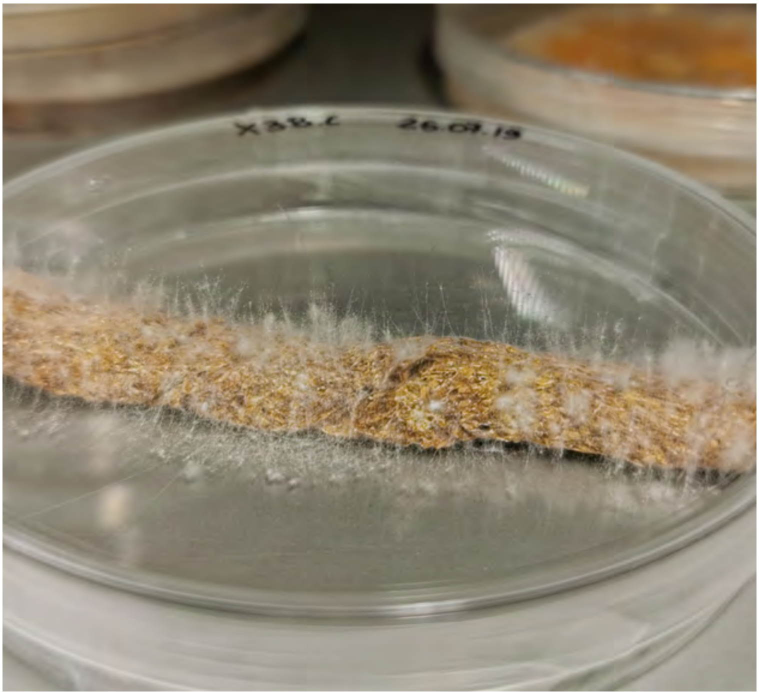


Plates incubated at 25°C, after 20 days of growth.

Room temperature conditions, after 62 days of growth.

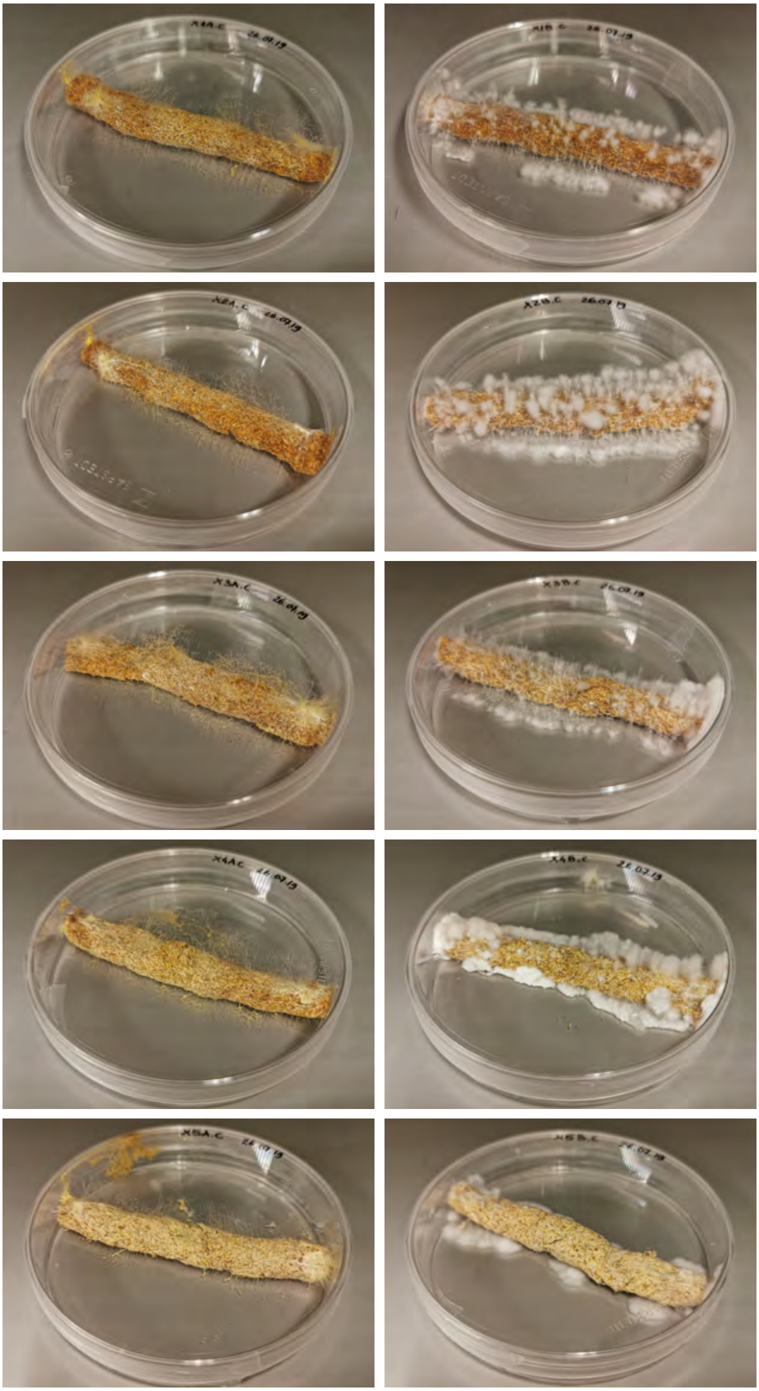


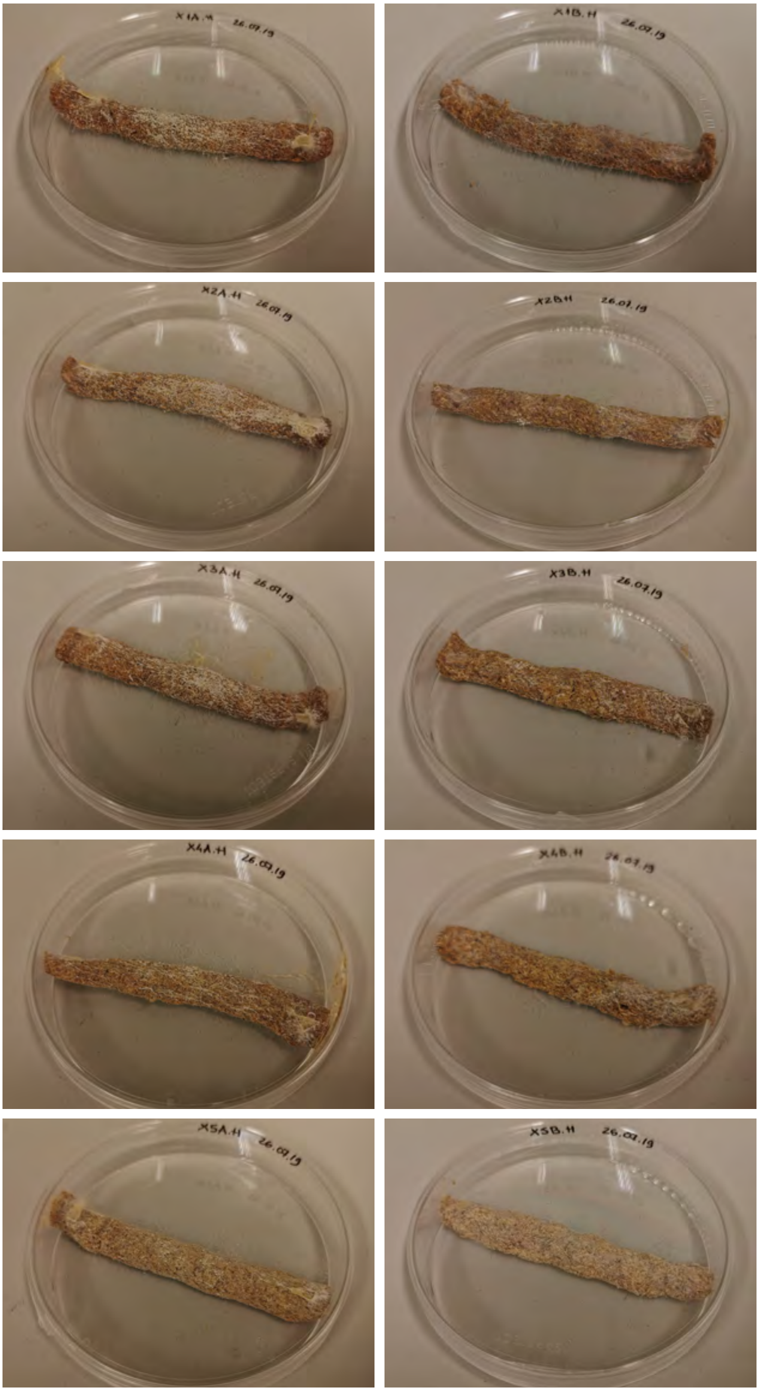




After 62 days of growth, we had already drawn the conclusions from the experiments, and the samples were left unchecked. However, we were surprised to discover the petri dishes where the mycelium has grown in beautiful morphologies, away from the substrate, and suspended in the air.

Room temperature conditions, after 119 days of growth.



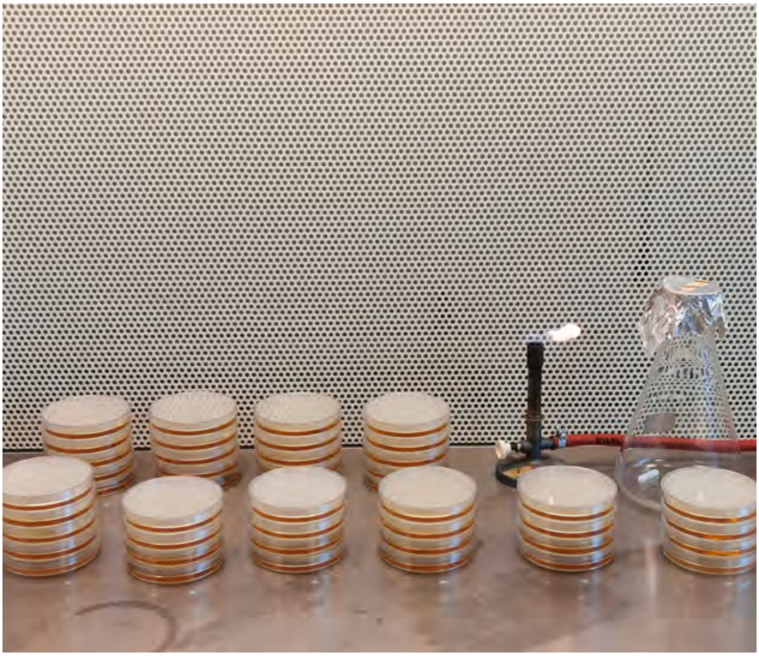


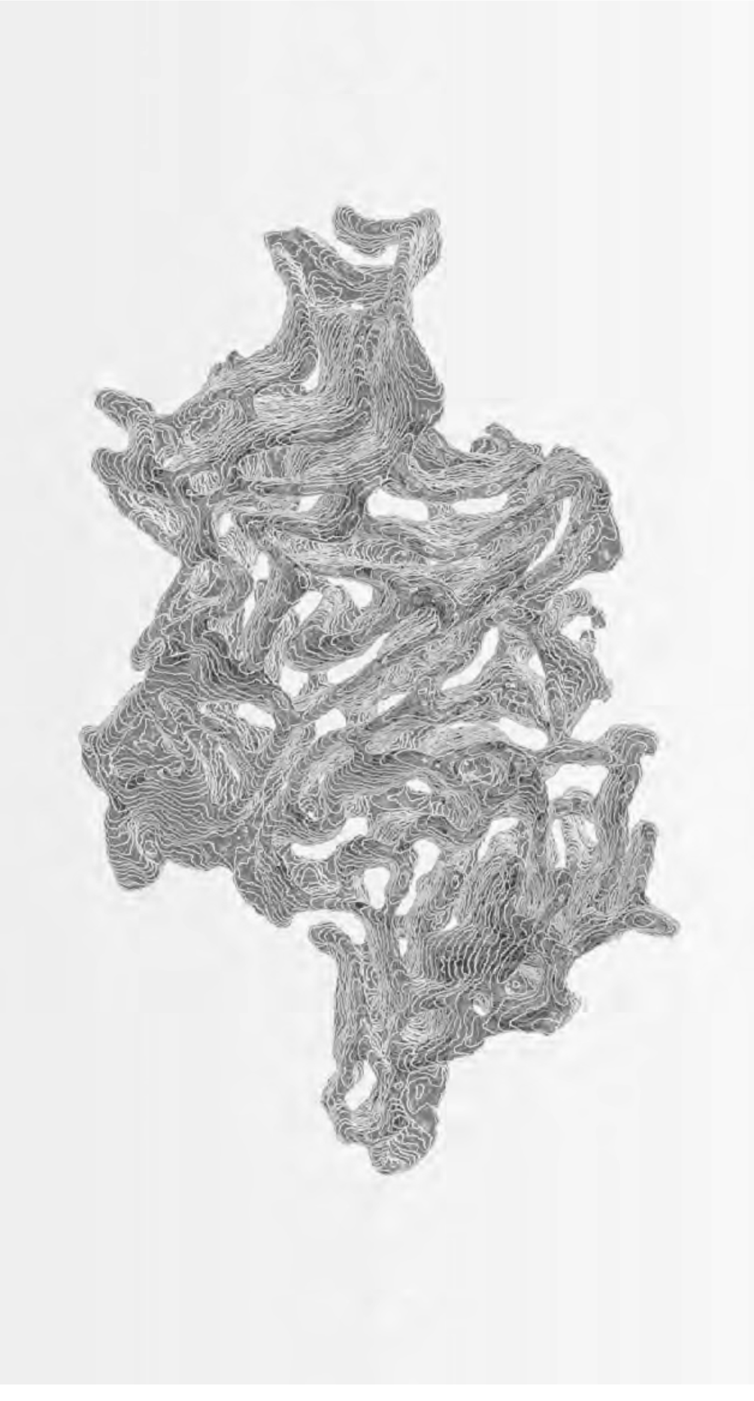
Plates incubated at 25°C, after 119 days of growth. These showed no further growth, and the fungus was inert.

Working with biofabrication implied a constant propagation of the fungal strain through new cultures. Throughout the project, a malt-yeast medium was used as it is does not have a highly elaborate preparation, and it has successfully worked with the strains that we used.

Every few weeks, a new batch of medium was prepared and plated.

A constant batch of fresh cultures was also kept, so that the fungi were vigorous and grew fast.



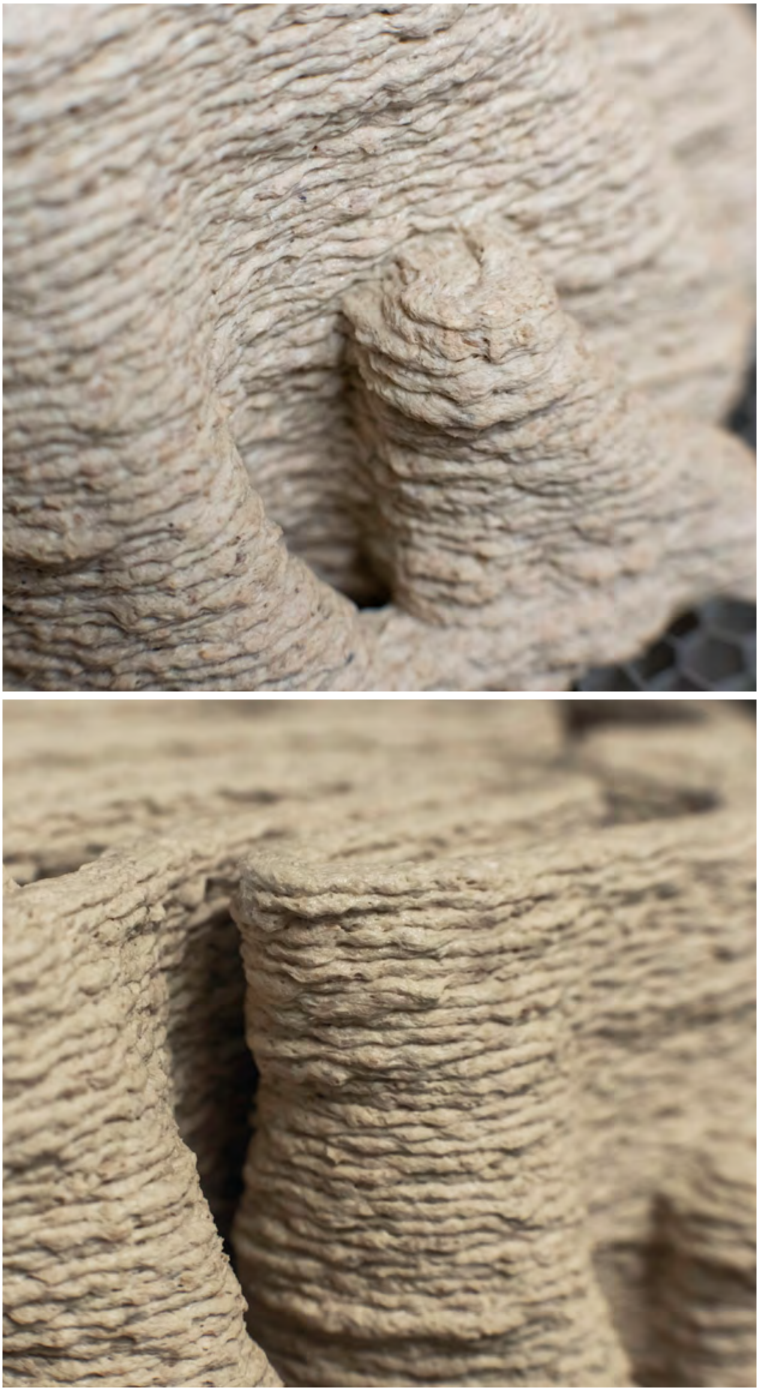


CT scan of fungal comb revealed the intricate internal geometry of its structure. It had relatively uniform depositions, as well as uniform gaps between the depositions. This has guided the next iteration of the design.

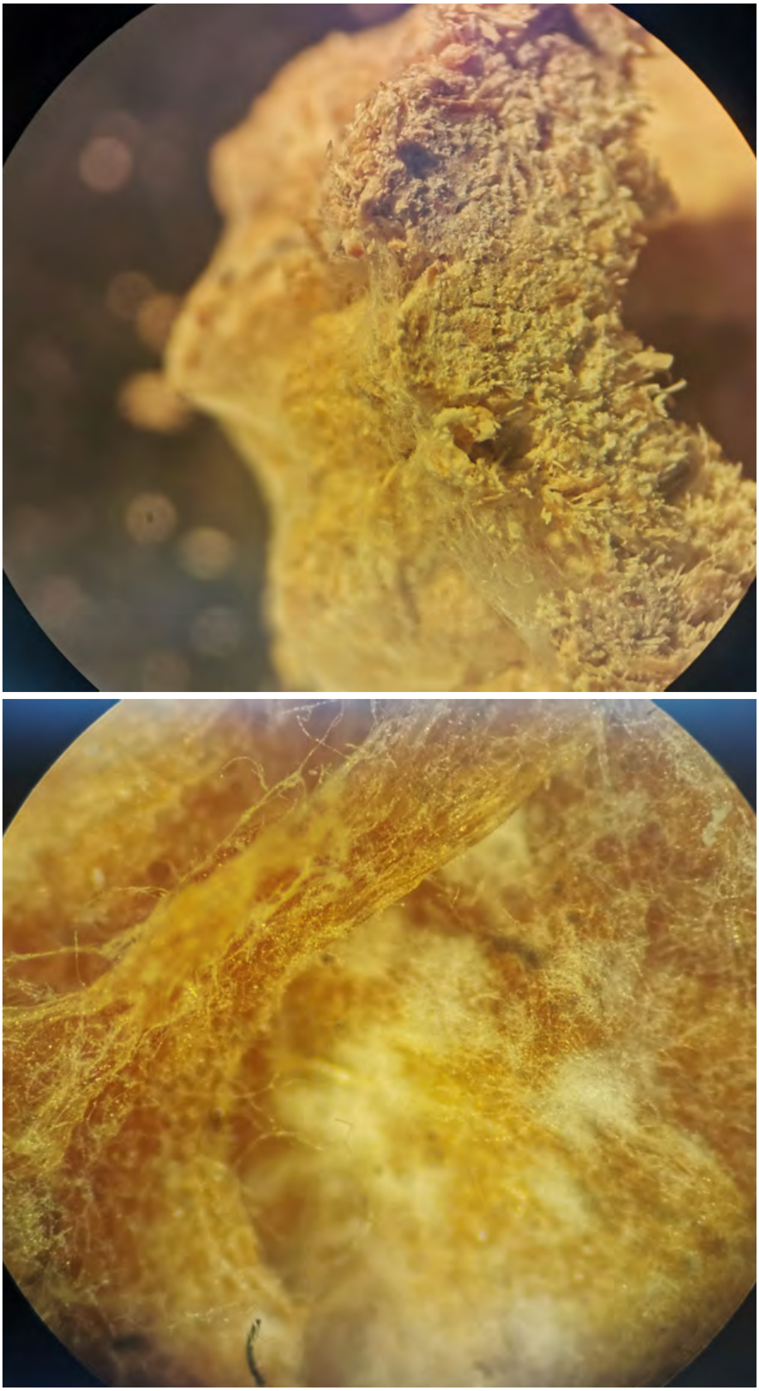
Initial tests 3d printing with lignocellulosic substrate, in reaction diffusion patterns.

Tests of another iteration of the reaction diffusion algorithm, at a different scale. Substrate recipe was updated to include clay.
Bottom image shows the printed test after it was dried out.

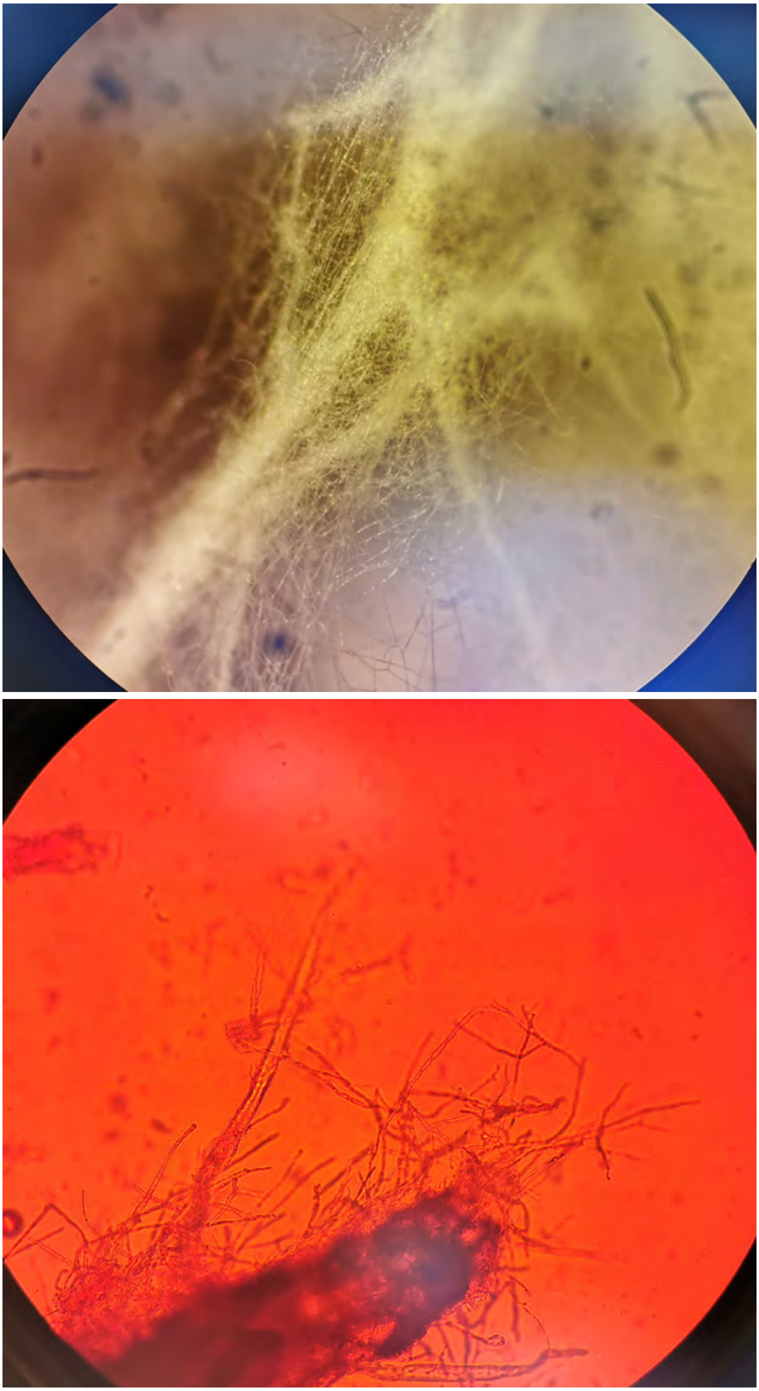
Early print with pulp, showing mycelium growing in the interstices. Print quality however is not ideal, with uneven layers.
Several iterations later, which included the addition of clay in the substrate, layer consistency has improved.



Result of the final substrate recipe, and protocol. Here, the images were taken immediately after the printing finished, and before the growth began. The printing quality had considerably improved.



A clean cut through a printed sample, in the direction perpendicular to the deposition direction shows that the mycelium is mostly distributed on the surface, with not much growth permeating inside.



Microscopy photography, showing the hyphal net on the surface of the printed sample.
Higher magnification of another sample, that has been growing for a longer time shows how the mycelium has fused the composite.

The scaling up process began by taking all of the largest beakers in the labs of the microbial ecology group, and loading them with substrate for incubation.
Although this provided good results, the more containers the pulp was spread in, the longer the preparation time, as well as the cleanup time.

Transportation of the beakers between the different rooms in the laboratory.

The second image shows the pre-growth inside the beaker.

The following improvement was to scale up the pregrowth container size. As the largest beakers in the microbiology laboratory were not large enough, we resorted to a construction staple: the bucket.

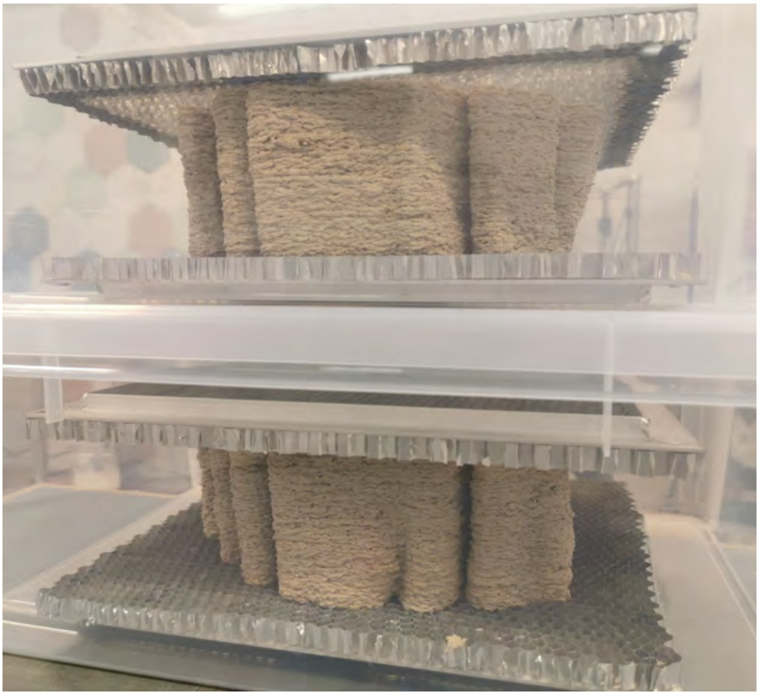
This highlights the scalar mismatches in the protocols for biofabrication, and the need for the development of new tools and methods that satisfy the unique junction of the microbiological need of a clean environment and architecture's hunger for scale.

The buckets with pulp growing in the incubator alongside petri dishes.

Along the course of this project, it has been quite entertaining to discover several points of connection to baking and fermentation in food industry. Here is the story of one. We had been mixing the pulp by hand, but as we scaled up the size of prints and their number, it had become both difficult to do by hand, as well as imparting a higher risk of contamination.

The best solution we found for mixing at this scale came in the form of an industrial dough mixer. Even the consistency needed from the pulp is similar to that of dough.

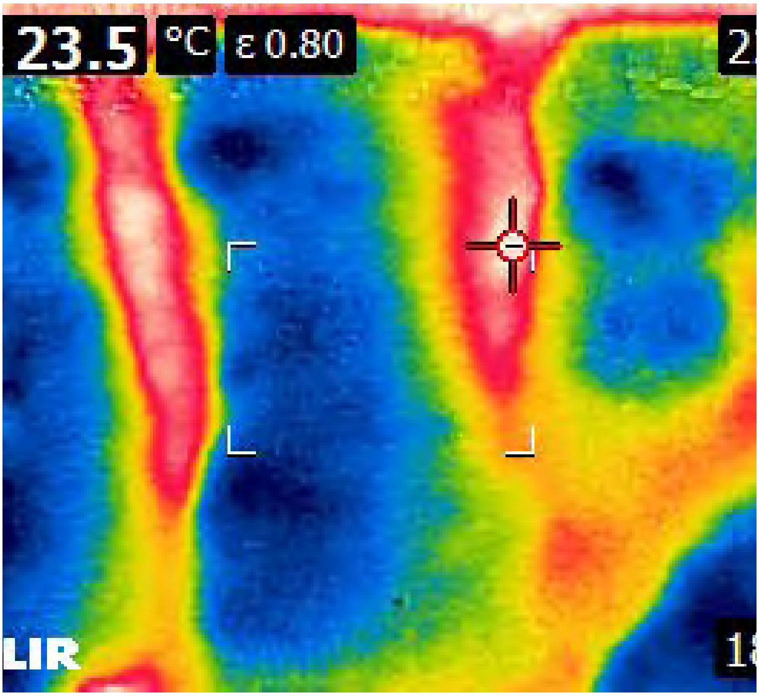
The longer the printing process would take, the longer the chances of contamination, as the printing took place in a workshop, where no sterile, or even cleaner than average conditions have been able to be enforced.
This is why we have been loading printer cartridges prior to starting the printing, as this allowed for uninterrupted printing.

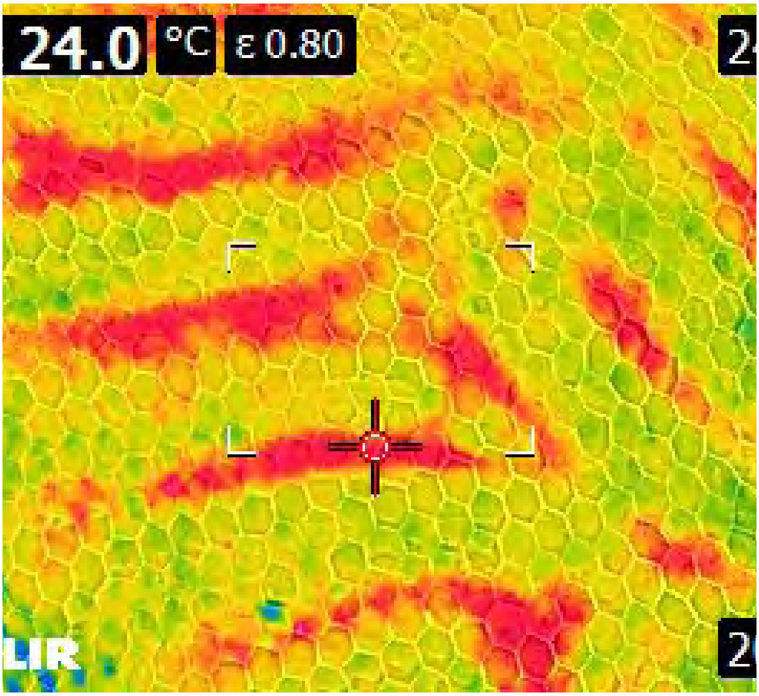


Setup with the 3d print sandwiched in between the meshes during the growth stage.
Below: first growth signs. At this stage the mycelium was wispy thin and visible only at the edges. However, the coloration of the pulp showed that the fungus was advancing with the colonization.

We loaned thermal imaging equipment from the Energy Building Department (thanks to Ricardo Bernardo) to see if we can learn anything new about the fungal metabolism through this lens.

We had expected to see a difference in temperature across the image. The metabolism of the fungus growing inside the pulp would generate heat, thus heating the pulp. However, this was not exactly visible in the thermal imaging. We assumed that this was the case because the exposure to room temperature cooled down the outer sections of living composite, and the inner ones have not yet cooled down. This could have explained why the high temperature was only in the inner ridges.



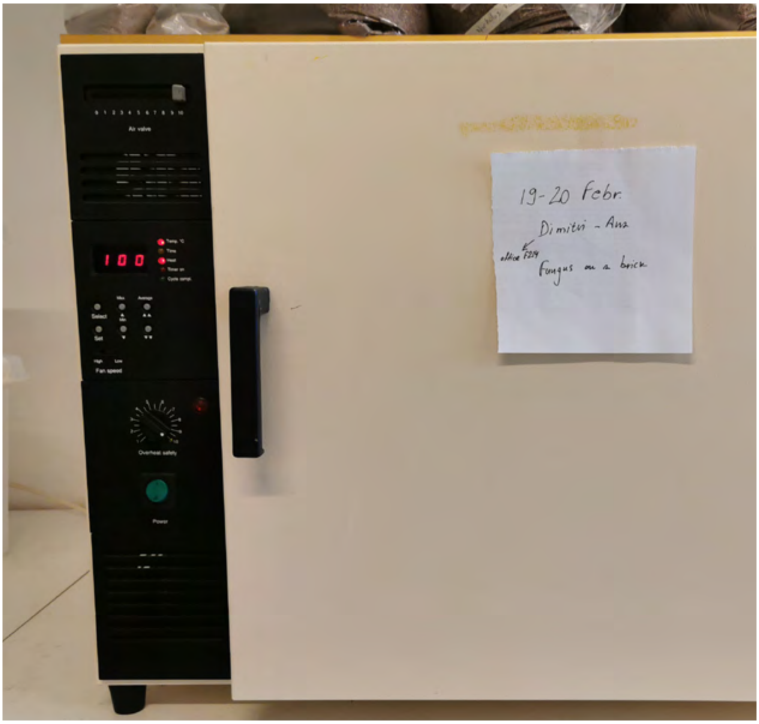


However, when we looked from above, it was interesting to see that the pulp was consistently and evenly cool, with no gradient from the core of the component to the perimeter.

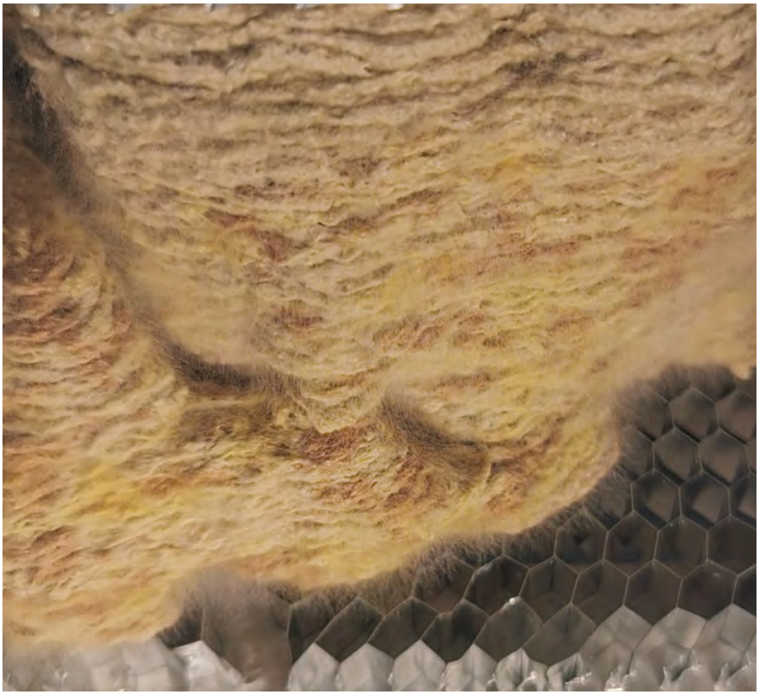
Instead, the high temperature spots were evenly distributed in the interstices. Perhaps this was due to the fact that most of the growth happened on the surface of the print, and therefore through respiration the air close to the surface was heated, and not the the substrate onto which the fungus was growing.

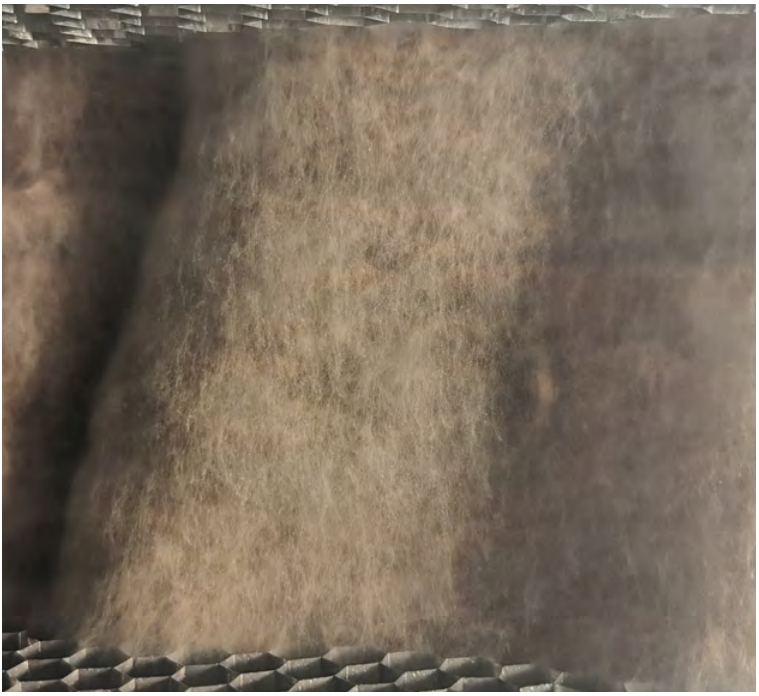
Printed and grown components being dried in ventilated incubators. These were placed either on a grilled shelf, or raised to facilitate even distribution of airflows.

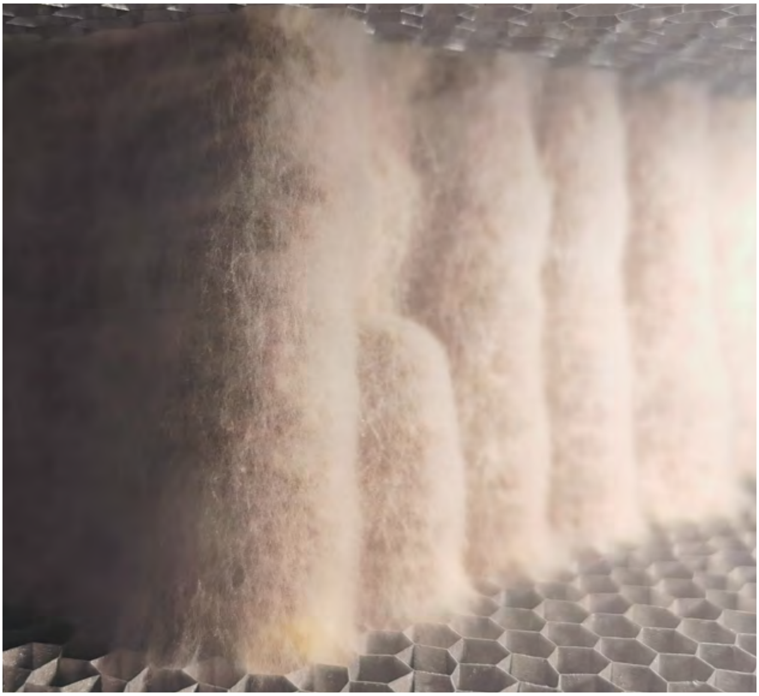
Below is the result after drying. Although there was local sagging where the print path cantilevered, it eventually corrected after a few layers, and there was no cumulative distortion.



There was a large variation of growth morphologies, even when conditions and protocols were kept consistent. These photo were taken during the growth stage.
The first image shows orange mycelium, as well as red coloration of the substrate.
The second image shows how the aggregation of mycelial threads has matured. These have gathered into chords, and could be heading on the way to form rhizomorphs. These are wide and empty hyphae that act as vessels, surrounded by hyphae that protect them.

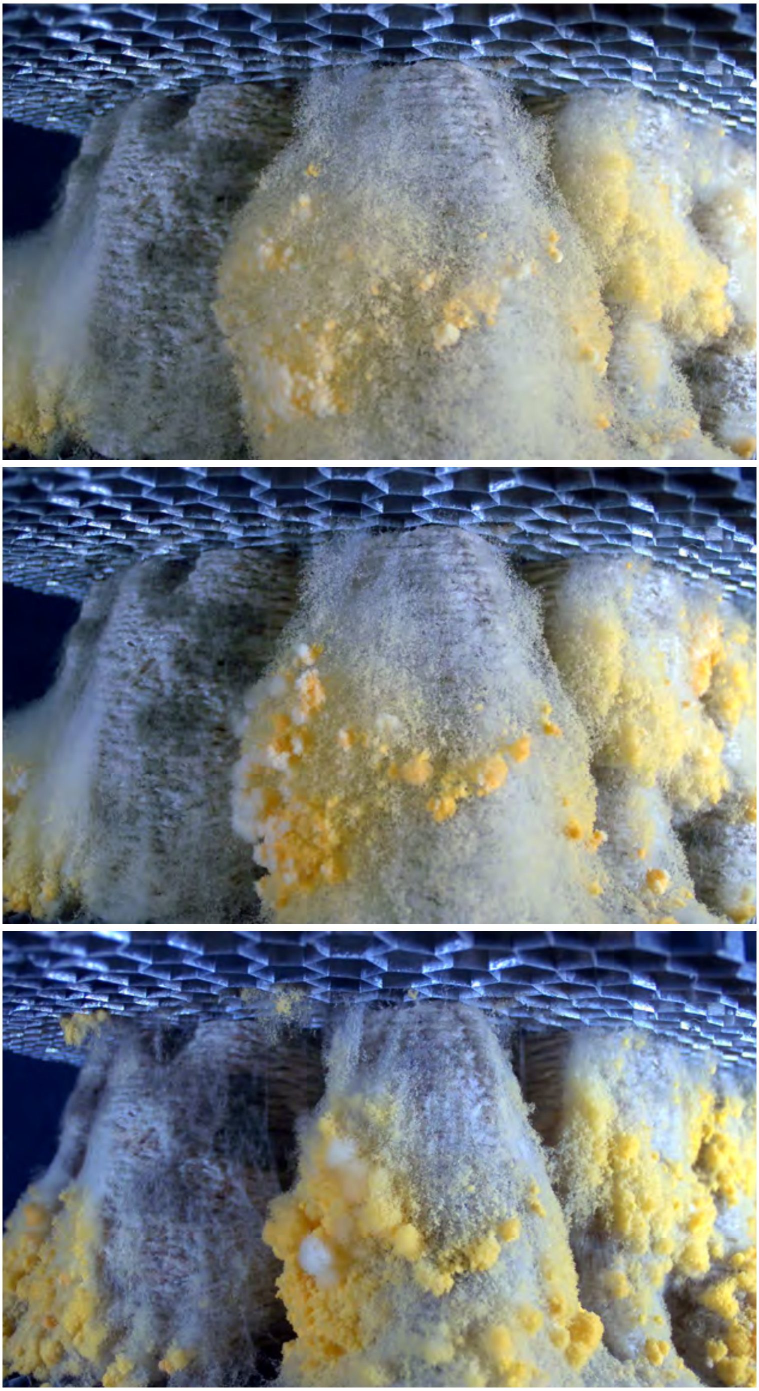






In some cases, the fungus grew forming aerial mycelium, resulting in a very soft and dense mat.

Even though we followed the protocol that we crafted and had several success with, we also had cases of contamination.
In the same conditions, setup, pulp recipe, sometimes within days apart, we would get a contamination failure. This was probably due to the fact that the final pulp mixing and printing took place in an uncontrolled environment, so ocassionaly some contaminants would be able to attach to the pulp, and sometimes take over the fungus.



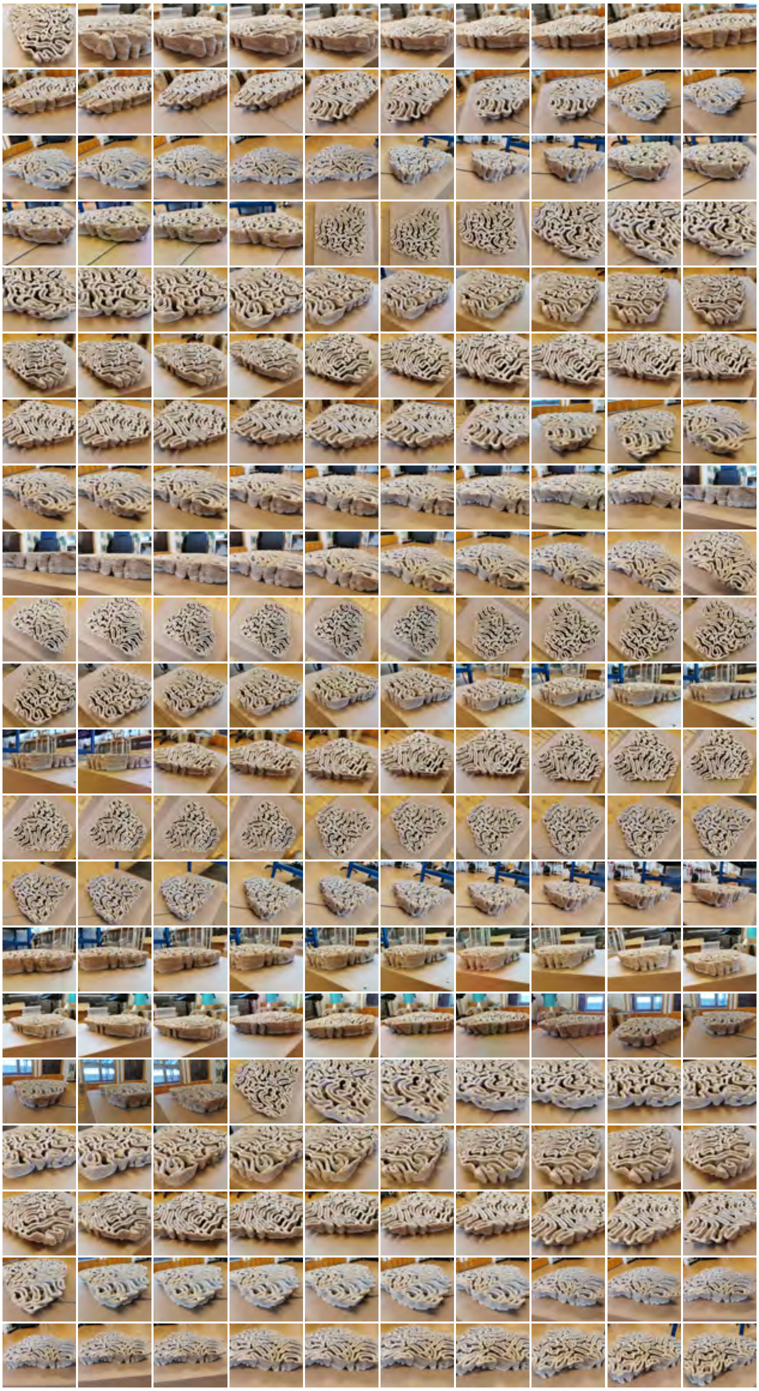
I have set up a timelapse camera to record the fungal growth on a component. However, it had inadvertently captured the growth of contamination. This turned out to be quite spectacular, with several species growing side by side, and blooms of color in sporulation.

After all the components have been dried, they were removed from the meshes and sanded lightly, to remove the growth and pulp that entered the hexagonal cells, as it can be seen on the image on the right.

Then we stacked all the components vertically, with a modified pulp layer in between them.

Although there were distortions in all components, the placement of the meshes during growth and dessication had limited the lateral deformation, and such the components aligned quite well in most places.

The assembled column incorporated the marks of the process and the time it had developed in. The pandemic had introduced travel restrictions just as some components were placed in the incubator for growth. This resulted in some bricks having had a longer growth time than others, so instead of 4 weeks, some have grown for 8 weeks. This resulted in some components undergoing a higher degree of biotransformation, which made them both shrink slightly more, as well as change the shade of the components. Other times, the fungus reacted differently to the substrate or other conditions in different bricks, as the photos on growth morphology have shown above. This also changed the final color of the component, as well as the surface texture given by the different types of hyphal growth. However, this lack of uniformity instead of being seen as a fault, it can be read as a sign of natural variation, just as the planks in a wooden floor can have color and pattern variation, due to age or other characteristics of the individual tree.

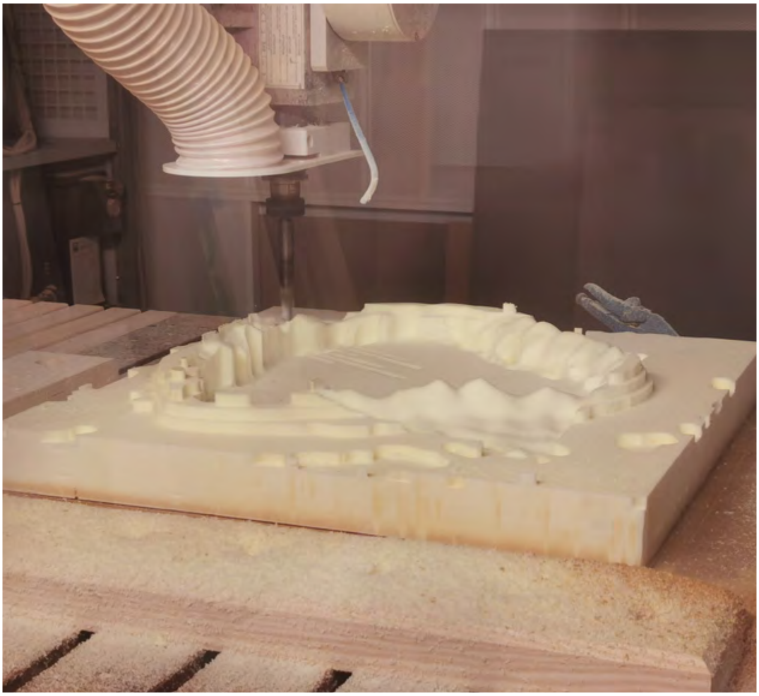


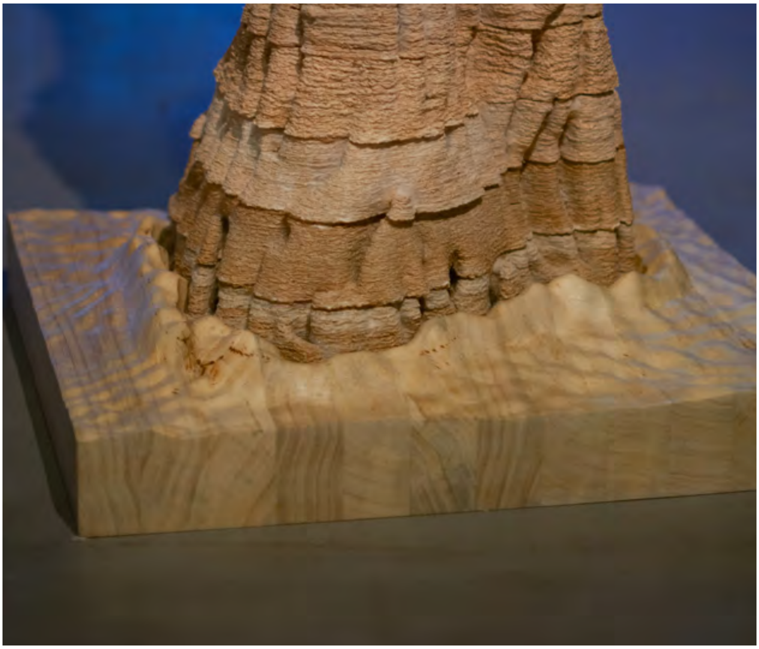
The last step was to make a base for the column. I wanted it to fit the column as well as stabilize it.

The first step for this was to have a 3d model of the bottom component. We did have the original model from which we have printed the components, but due to small changes during growth, drying, and sanding, the tolerance wouldn't be tight enough.

The solution I went for was then to scan the bottom component through photogrammetry. More precisely, the bottom part of the component.

I then CNC milled the base out of beech, on a 5 axis machine, in 3 passes with different drill heads.





The result of the base, after trimming the edges, sanding it down and impregnating it with solid matte wax.

Top image: Andréen, 2020.
Bottom image: @ SPARK, 2020.

5.5. Integrating transcalarity

One of the challenges with biofabrication in architecture is that of scalability. To bridge the vast scalar gap between microbiology and architecture, a transcalar approach can enable a more integrated performance. Through this, design at each of the scales in between is gradually constructed, and their interconnections are considered without homogenizing behavior and flattening the scalar difference.

In the context of biofabrication, scalar relationships are critical for several reasons. Biological organisms themselves operate at multiple scales, with fungi ranging from molecular to tissue levels. Understanding how these scales interact is needed to create biocompatible structures, as well as for the integration of structural properties with biological growth. When scaling to the size of architectural components, performance is enhanced if the scaling up maintains the complexity and specificity that are biologically required at smaller scales. Another reason is that biofabrication in this context involves multiple disciplines such as biology, material science, engineering, and design. Each of these disciplines often focuses on different scales, making an understanding of scalar relationships essential for effective collaboration.

In *Pulp Faction*, transcalarity was brought into the process of materialization by explicitly designing at several scales, allowing the requirements of each scale to influence others in a non-linear manner, beginning the non-hierarchical chain of effects from the microorganism scale. Steering the microorganism, crafting the material, designing the metamaterial, defining the bounds of components, and constructing the architectural element are all stages where each level's requirements have been made to interplay in an open system. This highlights the necessity for design and fabrication methods that can address these interconnected needs.

5.5.1. Sourcing as a link to global scales

The scale interplay becomes evident also from the perspective of resource management. Working with a fungal organism that operates at microscopic levels demands a thorough understanding of the substrate used, all the way down to its chemical composition. This understanding leverages the fungus' capability to thrive on industry by-products or waste from sectors like agriculture, while requiring a consideration of chemical constraints to ensure uninhibited growth. Consequently, this attention to sourcing is tied to the broader context of global supply chains. While all architectural materials require specific usage and sourcing considerations, living materials, sensitive to their composition, call for a higher level of care and knowledge in sourcing.

O(U)R Office of (Un)certainty Research (2020) unraveled the intricate layers behind the construction of a single house, revealing a vast network of sourcing spanning across the globe. This project, "A House Deconstructed", emphasized how contemporary architecture, largely unknowingly, draws upon a global orchestra of materials, labor, and processes. This project highlighted the richness of these transcalar interactions. From astronomical processes like supernovas having generated the elements needed to create materials such as steel to the human labor dispersed across continents, the house becomes a nexus of intricate relationships. These are key to a sustainable and informed practice in architecture, especially in the context of biofabrication. Material choice, even as an ingredient in a crafted material, becomes then a transcalar operation. As intentional and conscious sourcing in biofabrication is central to success, this might indeed bring a practice of care that is needed in the construction industry.

5.5.2. Transcalar links in structural performance

The growth of fungi and the characteristics they impart to the resulting biofabricated architectural element are not just determined by the substrate composition but are a product of a complex network of transcalar dependencies (Fig. 9). For example, factors such as surface hardness, hydrophobicity, tensile strength, and more are interacting to impart the performance of strength and durability, observable at macro scale. These are all taking place at different scales, as well as result from differently scalarly placed parameters, as it is in more detail explained below (Fig. 10).

Hydrophobicity is known to be a property of mycelium (Linder et al., 2005), and therefore it is imparted to fungal biocomposites to a higher degree with increased fungal coverage. This fungal growth which takes place at microscopic level, is intensified with increased oxygen access. This oxygenation is in turn influenced by the macro-level design of the component, as well as by the use of a print bed that allows airflows.

Minimizing distortion is necessary to ensure the structural integrity of the assembled column at macro scale. This deformation is an effect of fungal growth duration as well as the shrinkage during drying of the components. This drying shrinkage is proportionate to the amount of water in the substrate. Surface rigidity begins at the nano-scale production of extracellular polymeric substances, which is dependent on fungal growth and oxygen availability. The latter is a result of meso-scale algorithmic design. Tensile strength is an important contributor to the structural performance of the column. Here, it stems from a mix of factors: the extent of fungal permeation through the material, the fungal species used, and the geometry of the component. The extent of fungal infiltration is influenced by the material's depth, which in turn is determined by the printing nozzle diameter.

An important note is that certain desired effects often have contradicting requirements from the same parameters. For instance, while a high degree of extrudability is necessary for a smooth printing process, it can compromise strength and durability. Modifications that ease printing (such as a reduced amount of wood, smaller wood particles, finer fibers, increased amounts of xanthan gum and clay) can weaken the end result part. This negative correlation underscores the importance of evaluating the combined effects of each parameter change, rather than just optimizing for external factors. This complexity and the strong interdependencies within the system are key reasons why transcalar considerations are critical, as well as the fact that their interaction will be different in every case if a standardized, modular system is replaced with a mass customization approach (which arguably is necessary to facilitate and enable the benefits of this design system). Machine learning models are currently developed that predict complex interactions in bio-based materials for adaptive fabrication (Rossi et al., 2022), with potential applications in biofabrication, which could streamline its highly complex design challenges.

5.5.3. Addressing failures

Transcalarity can be instrumental in understanding failures regarding the performance of building components, and their constituting material systems. These failures stem from particular chains of effects, manifesting at specific scales. A transcalar perspective can often help

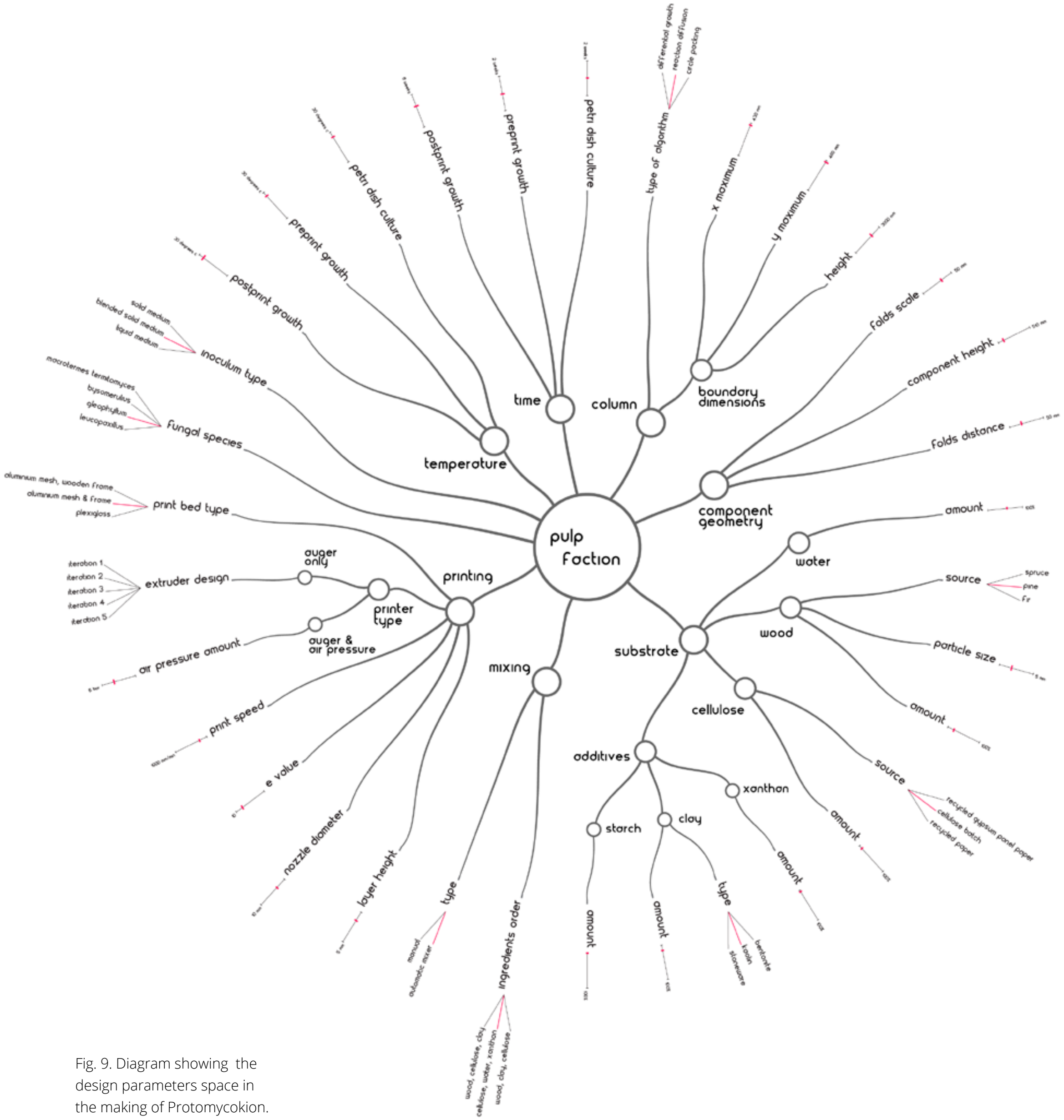


Fig. 9. Diagram showing the design parameters space in the making of Protomycokion. Source: Andréen & Goidea, 2022, pp 485.

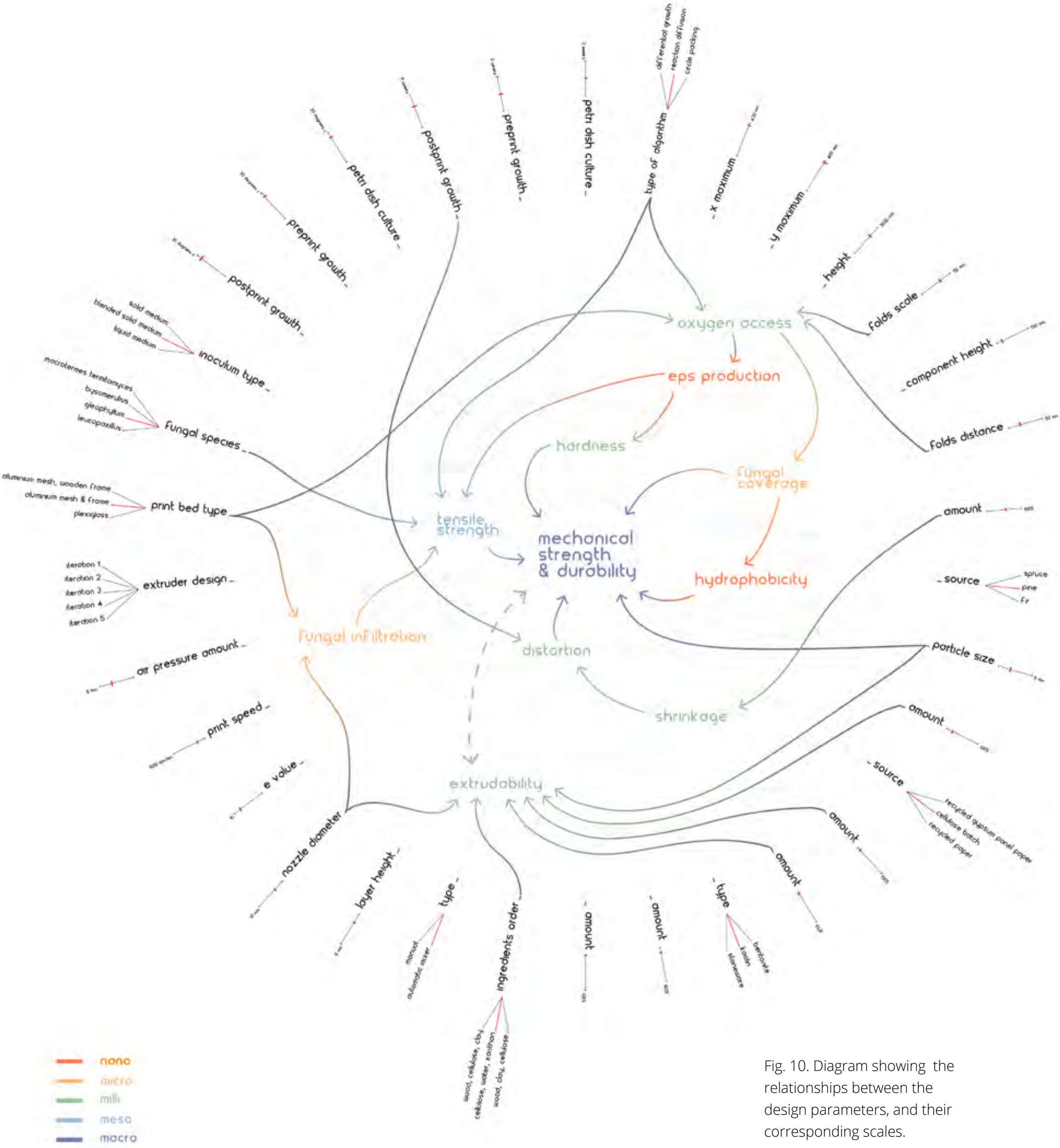


Fig. 10. Diagram showing the relationships between the design parameters, and their corresponding scales.

grasping how the causes are linked and suggest rectifications. One example is the delamination that occurred during the drying process, when fibers are extruded without being mixed with thermoplastics or setting adhesives. Addressing this can involve multiple scalar interventions, such as refining the material composition or enhancing fungal growth to strengthen inter-layer adhesion.

Another illustrative example encountered during the making of *Protomycokion* is contamination, where undesired species like moulds took over the colonization of the pulp. Contamination in fungal biofabrication can be considered a transcalar effect as it operates at and impacts multiple scales. Beginning at the microscopic scale, the introduction of unwanted microorganisms can scale up through growth and reproduction and disrupt the fungal growth and thus the material integrity. On a larger scale, contamination could lead to inconsistencies in the structural properties of the biofabricated component, as well as potentially negatively impact the health of the space in which it would be installed.

Addressing contamination through a transcalar approach involved applying strategies at different scales, as well as considering their interdependence. At the microscopic scale, the composition of the material was altered to not provide easy sugars that would aid the proliferation of molds. On the macroscopic scale, the conditions of the space in which the fabrication takes place were considered, and the protocol was refined to minimize the extent to which the living pulp was exposed to unsterilized air. The interplay between the scales was also considered: information from the microscopic scale informed design decisions at the mesoscopic or macroscopic scale, and vice versa. In this way, a better understanding of how fungal cells interact and operate at microscopic level informed more effective strategies for preventing contamination, even at higher scales. By increasing the time span of the pre-print incubation time, the fungus had spread to a higher degree, therefore reducing the potential of another species appropriating the pulp.

Additionally, the dimensions of the containers used for sterilizing the substrate affected the contamination. When the substrate was sterilized in larger volumes, the insulating properties of the pulp prevented the heat generated by the autoclave from fully penetrating the material. This resulted in portions of the pulp remaining unsterilized, which was suspected to have caused subsequent contamination. This issue was addressed by both downsizing the containers and reducing the density of the packed material within them.

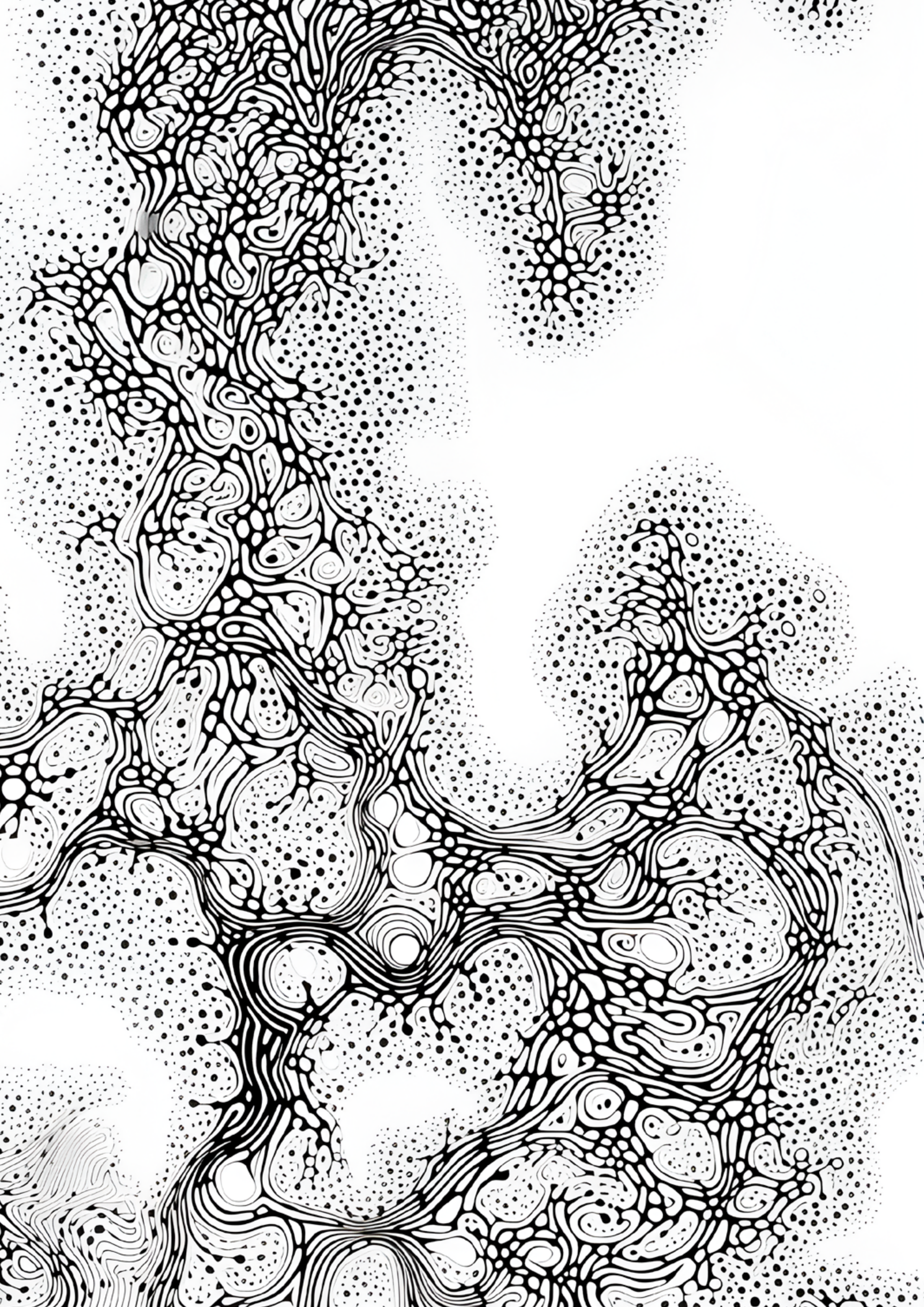
Structural failure caused by uncontrolled shrinking represents a transcalar effect in failures, as it affects both the component and the structural integrity of the final object. To mitigate this issue, shrinking was confined to the z-axis by incorporating mesh supports. Several prototypes were fabricated and measured after drying, revealing a 23% shrinking rate. This data was then integrated into the overall column design, which was extended by 129% prior to the subdivision into components and translation into g-code[8].

5.5.4. Conclusion

The *Protomycokion* demonstrator communicates the potential for scaling microbial processes to architectural dimensions, despite the presence of unresolved questions and opportunities for refining the method or exploring alternative fabrication techniques. The range covered, from sub-millimeter to meter, suggests the potential for transitioning from a singular experimental structure to broader scales of production. Such transitions, moving from experimental micro-scales to expansive manufacturing have already been witnessed in various fields, including fermentation in the food sector and pharmaceuticals, and therefore are not out of reach.

In conclusion, the concept of transcalarity holds significant importance in *Pulp Faction*, and should be further implemented when considering the future development of additive manufacturing with fungal biocomposites. While parts of the current project involved manual integration of scalar relationships, computational design models present an opportunity to manage complex, multidirectional, and even negatively correlated relationships across multiple scales. As the field evolves, it becomes critical to employ computational methods that can holistically account for these manifold relationships. This can not only streamline the design and fabrication processes but also create a more robust system that can adapt and respond to various challenges and constraints at different scales.

[8] G-code is the most common computer programming language for CNC and 3d printing.



> *With all the holes in you already there's no reason to define the outside environment as alien.*
>
> - Jenny Holzer, 1983

6. Meristem Wall

This project investigates the role of a building envelope in the context of the wide scalar and geometrical possibilities allowed by particle bed additive manufacturing and computational design. *Meristem Wall* employs a series of generative algorithms to design performative geometries that manage several functions at the same time and in the same space. The project has concluded with a full-scale demonstrator of a wall section of 2.1 * 1.25 * 0.7 meters, realized with binder-jet 3d printing in sand, and with an inner membrane fabricated through CNC knitting.

Due in part to the demands for efficiency in industrialized building systems, building walls are commonly assembled from layers of different materials layered together, with each serving one purpose, resulting in composite structures. This approach contrasts with the functional emergence observed in nature. In biological systems, gradients and variation in material often dictate performance. However, when compared to the standardization seen in building components, performance is more commonly articulated through performative geometry.

This project explores such an alternative model to material layering, where geometrical specification instead takes on the main role of carrying performance. Functions that are needed within a building skin, such as structure, circulating water, distributing electricity, assembly, cladding, openings for light and visibility are all integrated in a complex geometry system. This negotiation of overlapping functions has been solved through computation, using a series of algorithms that are partly self-organizing.

The range of functions extends beyond what the standard wall typically supplies. Here, the building envelope is seen as a membrane facilitating exchange through a range of transport phenomena. Based on how termite mounds act as organs of respiratory exchange, a ventilation system that has been developed for architectural application (Andréen & Soar, 2023) is implemented into the wall.

This low volume ventilation system functions through a transient flow network that activates turbulence in the air volumes in and around the network, which leads to mixing and net mass transfer. The network opens up into niches on the building façade and thereby modulates their microclimates. Several scales and their integration have been targeted through design and managed through computational tools. These have been synthesized into the wall, which acts as a mediator of human needs, ecological needs, and the needs of the building itself. For example by moving humid air out, it prevents mold growth on the inside, while creating a more comfortable indoor environment, and at the same time supporting plant growth on the external part of the wall. In this way, scales wider than the building are addressed, through conceding space for diversity in urban ecosystems.

6.1. Extended ecosystems

While an important goal of *Meristem Wall* was to achieve functional integration through design, its primary role was to regulate airflows throughout its structure. This led to a twofold interaction with the surrounding urban environment: it serves as a proposed extended ecosystem on one hand, and on the other it connects its indoor space to the external world.

The approach of removing the standard watertight and airtight boundary between inside and outside brings some understandable questions. Especially when instead of a wall separating, a porous membrane connects with a space dedicated to biodiversity, there can be concerns regarding microscopic to macroscopic "wild beasts" infiltrating human dwellings. To address this, we can look to investigations by biologist Robert Dunn, who maps the ecosystems found in homes. Although it might seem that indoor spaces in urban contexts are free of organisms outside of humans and their pets, potted plants, and the occasional unwanted flies, he has found that around 100,000 species are generally residing on average in a human home (2018).

Furthermore, he posits that there can be no sterile spaces where human life is present. Even on the ISS, where massive sterilization and decontamination efforts have been employed, this has not succeeded: a study found more than 12,000 distinct microbial species, including pathogenic ones (Lang et al., 2017).

This highlights the unintended consequences of creating what is supposed to be an impermeable barrier between the indoors and the outdoors. The aim may be to keep "nature" out, but what actually happens is the formation of an undesired ecosystem. Within this contained environment, hundreds of thousands of species still make a habitat out of the typical home, including several human pathogens, that now have no competition or predators in the modified indoor chain.

At the same time, unbalanced ecosystems are created on a wider scale. A recent study by Greenspoon et al., (2023) reveals how far-reaching this is. They estimated that out of the entire biomass of land mammals on the planet, there are only 1.92% wild animals remaining. The rest of more than 98% consists of humans (37.51%) and domesticated mammals (60.57%). To put it in perspective, the mass of all domestic dogs is now equal to the mass of all wild land mammals; the "wild nature" "out there" is rapidly disappearing. Although land mammals are only part of the key numbers on global biodiversity, these figures are telling of the anthropogenic pressures.

Urbanization has been identified as one of the main causes for the decline of several threatened and endangered species (Miller & Hobbs, 2002). Because of this, there is a need to conserve species and provide habitats for biodiversity. As cities, their agricultural and other industries annexes keep extending, it is becoming more difficult to secure land that is exclusively dedicated to conservation. Before suggesting a way forward, two types of ecosystems in response to this need will be defined, as they are described in restoration and conservation ecology theory. These are novel ecosystems and designed ecosystems.

Novel ecosystems are made where the effects of the industrial activity of the Anthropocene have made changes that cannot be restored back to the original ecosystem through the tools of classical restoration. These are oftentimes in large areas that have been heavily degraded or destroyed, for example by surface mining or long-term cultivation followed by abandonment (Higgs, 2017). The novel ecosystem then is a large-scale intervention, for example by the creation of wetland in an abandoned mining site. Importantly, for an ecosystem to be novel, it needs to have developed a metastable population, and an evolving landscape that doesn't rely on extensive human intervention (Higgs, 2017).

Designed Ecosystems on the other hand are ecosystems that are heavily and constantly managed to achieve a clear goal that had been set beforehand. One example of a designed ecosystem is a green roof. This approach uses "ecological principles to inform explicit designs that produce functional systems primarily for human benefit" (Higgs, 2017). These can be aimed at reducing urban island effects, minimizing agricultural inputs, managing stormwater flows, filtration, cooling, or aesthetic purposes.

New types of spaces are needed for biodiversity. This is not only because of the growing urbanism, but because areas of intensive human development sometimes are biodiversity hotspots around the world, and can even completely overlap with the entire distribution of a species (Soanes & Lentini, 2019). The perception of urban environments as opposite to "natural" has held back the potential to use urban areas for the supporting biodiversity, and this is visible in the urban planning regulations, and conservation zoning that exclude urban areas from their planning. To make this even more difficult, space in cities is limited and expensive. The few existing green or undeveloped plots within cities are under pressure to be infilled, oftentimes with high development potential which brings the cost too high to be kept unbuilt.

All these pressures point to a need to create new solutions inside cities where ecosystems can thrive, without using developable land. As Soanes and Lentini write, "failing to recognize the value of unconventional spaces can lead to the degradation and destruction of important habitats” (2019, pp. 228).

In this context I propose the term *extended ecosystem*, to define a new type of environment that sits in between the novel and the designed: an extension of a designed ecosystem. This type of ecosystem is hosted in unconventional spaces inside cities, and even though it is initially designed, through time and through the “unmanaged interplay of native and exotic species and shifts in environmental conditions” (Higgs, 2017), it becomes not novel, as Higgs suggests, but extended. It does support human needs and other functions belonging to human habitats as a designed ecosystem, but it also prioritizes biodiversity and ecological restoration, and doesn’t require constant maintenance, as its goals are not fixed and is allowed to evolve as a novel ecosystem. Extended ecosystems are meant to be integrated into architectural structures in urban settings that are not currently used for any purpose, such as external building surfaces. The aim is that they reach self-sustainability with the passage of seasons, with the year cycles of local condition. These ecosystems are planned to evolve to be more than lawns on green roofs, with the intention to support an urban wildlife that goes beyond pigeons, rats and seagulls that feed on food waste. They enable richer mixes of life and life forms.

The benefits go beyond the preservation of species – they allow people to engage with nature and benefit from the psychological as well as other types of well-being, such as: air purification, thermal buffering, acoustic comfort. Furthermore, placing conservation sites so close to urban communities, even though it can be dangerous for the threatened species, it can also raise awareness of the condition of the species, and enhance ownership, participation, and stewardship in the natural environment, which are all important in environmental policy (Soanes & Lentini, 2019).

6.2. Particle bed 3d printing and multifunctional integration

Particle bed 3d printing includes several types of technologies of fabrication that are relevant at architectural scale, such as binder jetting (BJ), selective cement activation (SCA) and paste intrusion (PI). There are different types of material combinations currently employed by this technology.

One of the earliest implementations of this technology at architectural scale was done by Enrico Dini, with the D-Shape printer (Dini, 2009). The *Digital Grotesque* series by Hansmeyer and Dillenburger (2013) explored the implications of the very high resolutions afforded by the technology used, through the fabrication of full-scale architectural spaces. This was produced through BJ with quartz sand and furan binder, sharing the same materiality with *Meristem Wall*.

Fig. 11. Digital Grotesque II. Grotto at the Centre Pompidou Photo: Fabrice Dall'Anese. Source: © Digital Building Technologies, ETH Zurich.

Currently, this fabrication method is mainly utilized in the metal foundry industry to create molds for casting. The present materials and settings are refined for this role, ensuring the mold withstands the high temperatures of molten metal casting, exhibits the porosity necessary to vent fumes, and maintains a brittleness that facilitates clean breaks without harming the cast pieces. While these criteria are well adjusted to the requirements of foundries, they don't necessarily align with the ones needed for the direct production of architectural parts. Within construction, there is ongoing research into alternative materials compatible with this production technology, including cement, sodium silicates, magnesium oxides and geopolymers.

A bridge was built and installed in Madrid by Acciona and Dini, in collaboration with Institute for Advanced Architecture of Catalonia (IAAC) using a cementitious mix. This is one of the largest scale structural prints with this technology, measuring 12 meters long (2021). It employed computational design to maximize structural performance.

A more recent project employing the SCA technology is the *BREUER X AM* demonstrator, done by a collaborative team in the Transregio 277 Additive Manufacturing in Construction, with The Technical University of Munich, The Technical University of Braunschweig, and additive tectonics (Dörfler et al., 2023). The project resulted in a large-scale prefabricated concrete building element, measuring 3 * 1.8 * 0.75 meters, the entire element being printed in one piece. The material composition utilized Portland cement combined with lightweight aggregates in the form of expanded glass granulates.

Aiming to integrate multiple functions within a single structural element, much like the *Meristem Wall*, the *BREUER X AM* demonstrator focused on eliminating the need for multi-layered building systems. It aimed to integrate various functional requirements such as structural stability, thermal insulation, and solar exposure control. The inclusion of a cellular structure provided a setup for the later addition of insulating materials, designed to improve thermal performance. The demonstrator also integrated joint detailing, and the incorporation of a lost formwork, for the installation of steel reinforcements and the casting of grout-based concrete (Dörfler et al., 2023). The project included significant material and process development to be able to fabricate in one piece a cement with SCA technology, paving the way for customizability and site-specific adaptations to be integrated through additive manufacturing technologies.


Fig. 12. BREUER X AM demonstrator. Source: © additive tectonics, 2023.

The *Swatch Headquarters* by Shigeru Ban Architects employs entirely different materials and construction systems from *Meristem Wall*. However, what ties the two projects together is the approach to integrating multiple functions within the building envelope. The timber frame goes beyond its role as a façade, integrating several technical functions through a complex network of cables, including heating, cooling, and ventilation. The structure incorporates of ETFE panels as well as an acoustics layer (Gonchar, 2019).

Originally, the building envelope had a thickness of 1.4 meters, which was deemed too bulky for one of the world's largest timber structures with expansive spans. The solution was found in a comprehensive redesign of the envelope that focused on the interfaces between the structural elements, the cladding, and its various mechanical, thermal, and acoustic systems. Through tight coordination of the different functions, they reduced the envelope's thickness to 0.9 meters (Gonchar, 2019).

6.3. Methods

One of the main ambitions of *Meristem Wall* was to explore and demonstrate how multi-functional integration can be achieved in a building envelope though the geometric structuring of the wall as a functionally graded metamaterial. Due to the geometric complexity of such a metamaterial, various forms of algorithmic self-organization were used. For the fabrication of the demonstrator, a sand-based binder jet 3d printing was employed, which results in parts with strength sufficient for structural architectural components and which is also capable of high precision of sub-millimeter resolutions. This high resolution can be an enabler of articulate functions, while at the same time a challenge for the current tools and methods for designing at multiple scales.

Since the wall was materialized in sand and furan binder, design in this project is not emergent from these material properties, except for fabrication, compression strength and assembly parameters influencing the design. However, this does not imply that materiality plays a passive role in the project; to the contrary, air is an active material deeply driving the design process.

Air is considered the main material in the material computation framework of the project. It serves as an active agent that informs the design, and in turn is manipulated by it. Drawing inspiration from the biological precedent of the termite mounds, which function as a mechanism for homeostasis and the exchange of gases and energy, the wall aims to facilitate a similar exchange between its interior and exterior environments. Thus, the wall is constructed to enable a specified behavior of air flows, explained in the following two considerations.

Firstly, a primary focus of the design was on the specific conditions for creating air turbulence. Through induced oscillations, the reticulated network geometry, with its tortuosity and obstacles due to branching, is a generator of transient flows, which then induce mass transfer of air within and through the wall. These transient flows and the ensuing mass transfer of air are not random but are relying on a set of conditions to be met. These conditions include the proportions between the channel diameter and length, the angle of the reticulation, and the amplitude and frequency of the induced oscillations.

Secondly, since it directly connects the interior architectural space with the outdoor environment, it aims to block laminar flows, such as those caused by wind. According to Poiseuille's law, laminar flow is directly proportional to the fourth power of the channel radius, and indirectly proportional to the channel length. To reduce cross flows, the wall features a network of narrow and elongated channels that reduce laminar air flow due to air viscosity and friction along the channel walls. The tortuous channels within this reticulated network further limit steady air flows (Andréen & Soar, 2023).

Therefore, the wall was designed to both limit and enable air flow selectively; its network of channels is narrow and long enough to suppress laminar air flow, while low energy activations of an oscillator embedded within can drive air transfer. Through fluid dynamics enabled by computational design, the wall is more than just a physical barrier; it becomes an active mediator of air flows, bridging the indoor and outdoor environments.

The following describes the methods for the computational design, digital fabrication of the wall and inner membrane, and assembly for the demonstrator *Meristem Wall*.

Fig. 13. Prototype.

6.3.1. Computational design

The aim of this project was to demonstrate at 1:1 scale how functional integration across multiple scales simultaneously can take place through a combination of algorithms bridging self organization and highly customized solutions with top-down control and standardized solutions. The resolution of generative algorithms has been specified to include several scales of operation and resolution. To achieve the requirements needed, a set of three nested algorithms was combined, where each worked with different datasets.

First, a particle spring network was created for the central axes for the channels. A reticulated network of channels was laid out to connect the inside of the wall with the outside. This network consisted of two separate sets of grids that did not intersect, and gave the topological structure required to achieve the desired capability to drive and generate mixing through turbulence. Then the shapes of the networks were altered with three sets of forces. First were internal forces that distorted the network so that the channels were never in a straight line. This resulted in a tortuous network, that, together with the narrow channels blocks or significantly reduces cross-drafts (Goidea et al., 2021). Second, the network nodes in the building exterior zone were attracted to the external boundary in a varied pattern so as to create differently sized openings that allowed for the creations of nests on the outside. And third, another set of forces repelled the network to make room for several functions needed to be integrated into the wall, such as windows, electrical pipes, water pipes, activation box, and connectors for assembly.

Fig. 14. Opposite page: Meristem Wall.

The resulting edges from the two networks were used to generate a volumetric model through an intermediary step of a continuous modified isosurface located at a variable distance between the two networks' edges. This logic is similar to the one used when generating a gyroid, although a gyroid only derives from a specific network. In a gyroid the distance between the networks where the isosurface is created is constant throughout the geometry at 0.5 (where 0 is tangential to one of the networks and 1 is tangential to the other). However, in this case the distance was gradually increased from the inside to the outside, and two surfaces with an inverse distance relation were generated. On the outside it was placed at 1, so that the surface opened up and connected with itself, while on the inside it was placed at the distance of 0.1 and 0.9 respectively, so that it created the narrow channel interior outlets that transport the airflow.

The final stage was a volumetric model. This was generated based on proximity to the isosurface, giving a voxel-distribution of a uniform thickness along the isosurface. It allowed the generation of a printable geometry and enabled further local manipulation of the object geometry. This was useful for detailing adaptations to standardized parts. In this way, connectors with very low tolerances were created, and snap-fit elements such as electric box, light switch and plug. The voxel model was also where the high-resolution detailing needed for bioreceptivity was introduced. This was done both through a variation in textures on the external side of the wall, as well as through the addition of porous and perforated pockets that allow for roots to attach to and grow through the wall.

6.3.2. Printing

The fabrication was done by Voxeljet AG on a VX4000 machine. This has a print bed with dimensions of 4 * 2 * 1 meters, a scale that is fit for architectural production, while at the same time reaching a resolution of 200 dpi. The wall could have fit to be fabricated in one piece. However, due to transportation and assembly factors, it was divided into 21 pieces that were separated in the print bed. The number of parts to be assembled was determined by the maximum weight of each part, which had to not exceed 30 kg, so that it can be handled by one person.

The post-processing was done by Sandhelden GmbH. The printed parts were infiltrated with resin, to reduce the porosity of the material and increase the part strength. The post-processing also included a weathering layer and UV coat so that it would not get deteriorated through extended outdoor exposure.

6.3.3. CNC knitted textile

The side of the wall facing the interior was enveloped in a custom-made CNC knitted textile. Besides adding a comfortable tactility to the interior facing area of the wall, its role was to attach to the end of the network channels, and act as a filter for larger particles that might be brought from the outside environment.

It incorporated 5 different knit patterns for the paneling, and 2 additional ones for the inlet area and the area in between the inlet rows. We collaborated for its fabrication, which was done by Mariana Popescu at ETH on a seven gage CNC industrial knitting machine, specifically a Steiger Libra 1.130. Loops of nylon strands have been integrated as weft in-lays in the knitting process, in order to fix the membrane to the inlets. The knit was done mixing 4 colors of threads in a gradient from light yellow to desaturated blue and purple.

The visual patterns for CNC membrane were derived from the geometry of the outer wall area. In the interior area, the position of the wall inlets was the driver of the placement of the high density knit patterns that filter the air that is brought in.

6.3.4. Assembly

The 21 parts have been distributed in 3 columns by 7 pieces in each column. To install them, slots for connectors in between two adjacent parts were set, in which wooden studs were inserted. For safety reasons, hollow tubes have been integrated in the design, in which additional reinforcement was placed. However, this solution was made for the purpose of easy assembly and disassembly, as the demonstrator functioned as an exhibition piece. For an architectural application, other solutions would be recommended instead, such as reinforced cast concrete, larger printed components etc.

A flexible polyethylene (HDPE and PE-X) tubing was inserted into the water conduits, as well as narrower polypropylene (PP) tubing for the electrical fittings.

The conduits were designed to maintain a smooth curvature through generative simulation of rod-like behavior. This facilitated the easy insertion of tubing after assembly and accounts for an ease of future replacement and maintenance. A lamp, a dimmer and an electric socket were then installed into standardized wall boxes which were inserted in and fixed to the printed housings.

6.3.5. Research by design

In this project, the research-by-design methodology employed throughout the thesis took the form of iteration, reflection and development mainly focused on the computational aspect of the design space rather than through physical prototyping.

Fig. 15. Interior textile and fittings, Meristem Wall.

Therefore, the main probes have been done in the digital space. While the early tests and experiments in this investigation were mostly digital, they are similar in nature to the material probes described by Ramsgaard Thomsen and Tamke (2016). Working with the simulation engine Kangaroo for Grasshopper, developed by Piker (2013), form-finding took place through physics-based material behavior. Here, an early probe aimed to simulate the wet wool experiments previously done by Frei Otto (1988). However, this did not result in the desired morphology, and even though it generated minimum pathways from a network, a network topology was needed to be maintained. In response, we developed a custom script using custom forces on rods.

Other probes investigated how to manipulate the isosurface parameters in order to obtain openings for windows. We wanted these to not be a result of Boolean operations, but to work within the logic of the network and its isosurface bounds, so several probes investigated this aspect. There have been some material probes concerning the production of the CNC knitted membrane, to test its attachment to the wall inlets, as well as different knit patterns.

After having a working computational setup with the three nested algorithms, we planned the production of a physical prototype. Its aim was to clarify questions concerning minimum wall thickness for this particular geometry, but also ease of unpacking and handling. The prototype was fabricated at ETH Zürich, with support from Mathias Bernhardt.

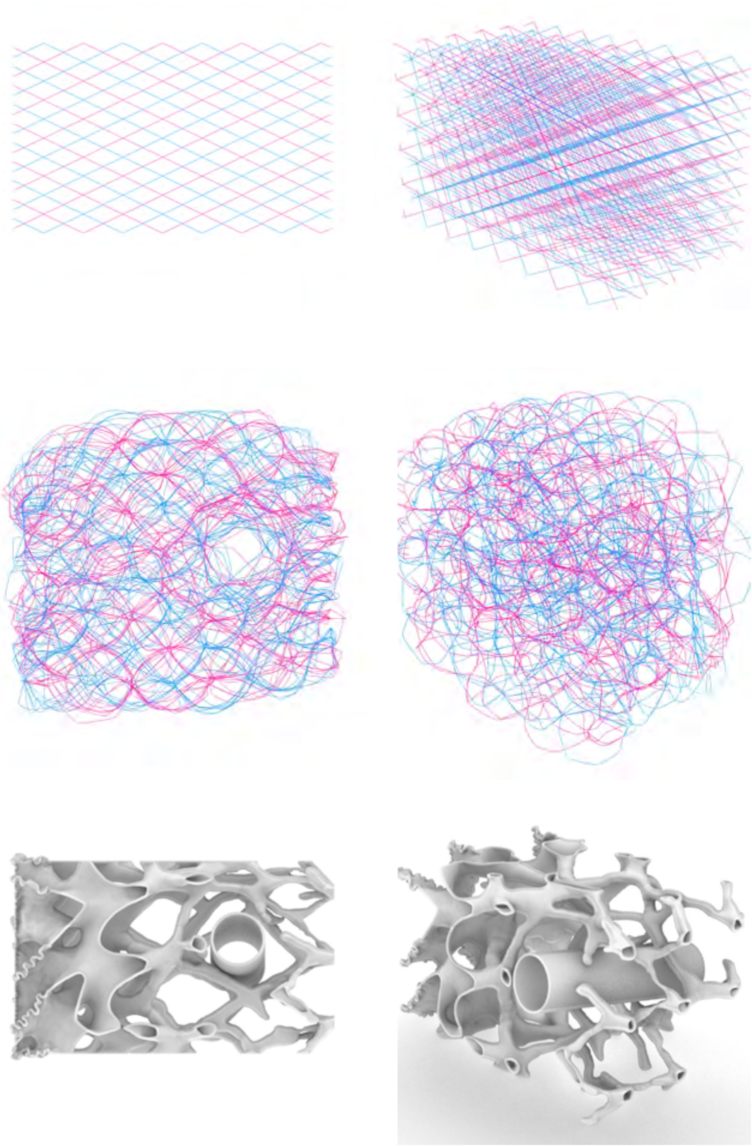
The outcomes of the prototype fabrication demonstrated the feasibility of unpacking, particularly with regards to loose sand evacuation from the internal channels. The prototype suggested that the brittleness of the material was particularly problematic for cantilevered single elements, while the wall thickness was sufficient for handling. Consequently, we reduced the scale of the network lattice, increasing the overall stability.

The production of the physical prototype also tested the scalability of the form-finding algorithm. The generation of the particle-spring configuration for the prototype of 600 * 400 * 400 mm took more than one hour to calculate, which showed that a new computational strategy was needed. The further development and scaling up to a full-sized wall demonstrator were then moved to Houdini SideFX. Here we built a custom script with Particle Operators (POP) to simulate the particle spring network. As this software that is optimized for multi-threading, the equivalent script ran significantly faster in this environment.

The demonstrator tested the resolution capabilities, with tubular geometries as small as 5 mm, and with snap-fit tolerances of 0.5 mm. Most have been able to be materialized successfully without breaking, although some network channels have fractured, during the transportation, assembly, and disassembly.

6.4. Visual journal

The visual journal of *Meristem Wall* is different from that of *Pulp Faction*. Where the former was heavily material, *Meristem Wall* experiment took place more in the digital realm. Consequently, the journal presents the digital journey and development, as well as the textile fabrication.



Meristem Wall began with the design and planning of a small section of a wall, that would cross from the interior to the exterior. This early prototype was based around two offset networks. These were simulated as a particle spring network to add tortuosity, repel the networks from each other, and repel from a central cylinder that represents a pipe going through the wall.

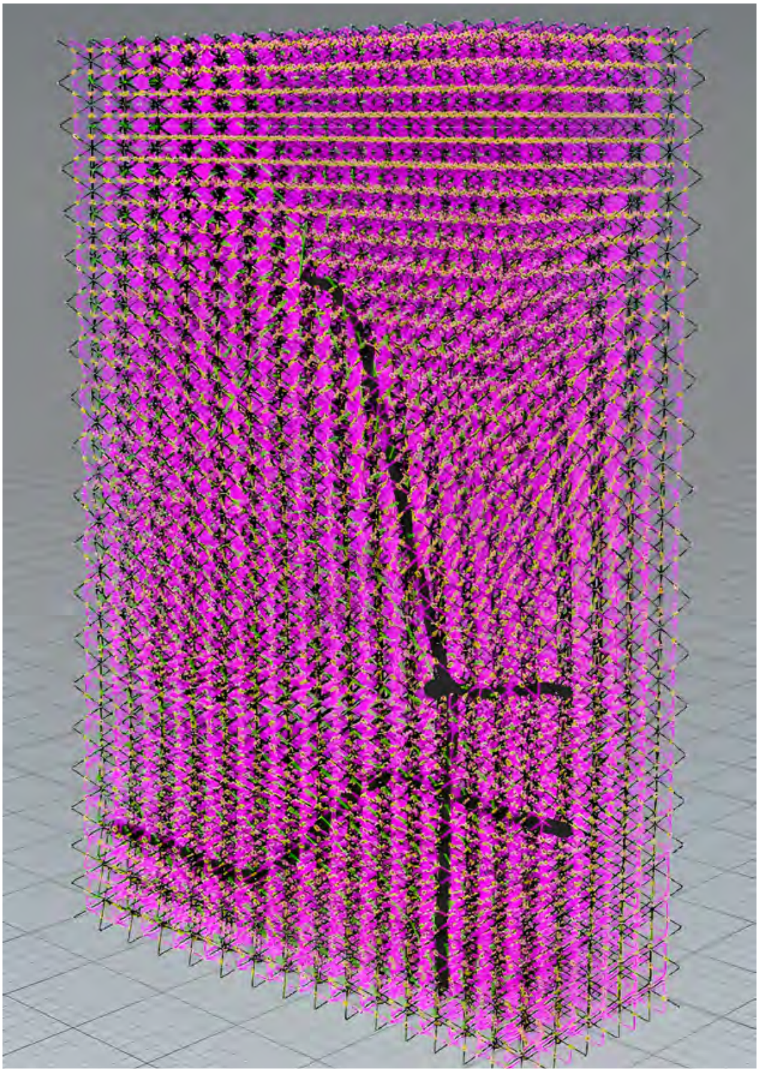
Top: Initial network connections. Middle: Relaxed particle spring network based on initial network. Bottom: thickened isosurface generated from networks.

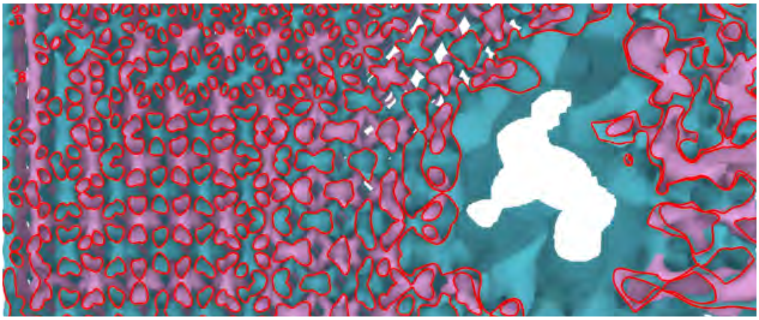
The prototype was printed at Digital Building Technologies, ETH Zürich, with the support of Mathias Bernhard. The photo shows the unpacking of the prototype.

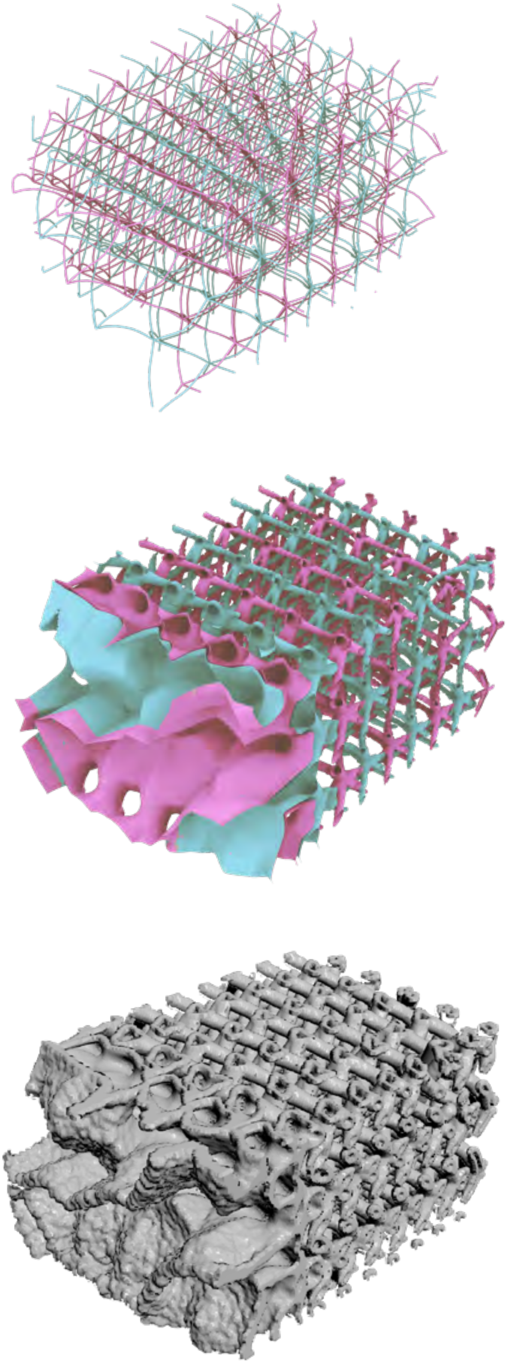
Prototype after unpacking and de-powdering. The interior side had a flat surface, as we thought this was necessary to support the channels that were cantilevering inwards. However, in the following iterations we increased the density of the networks, which strengthened the ends so we could remove the flat inner surface.

Particle-spring network in the initial position. The electrical tubing and pipe are visible inside the wall, through the network.

Below is the isosurface derived from the two networks, with a preview cut section in red.

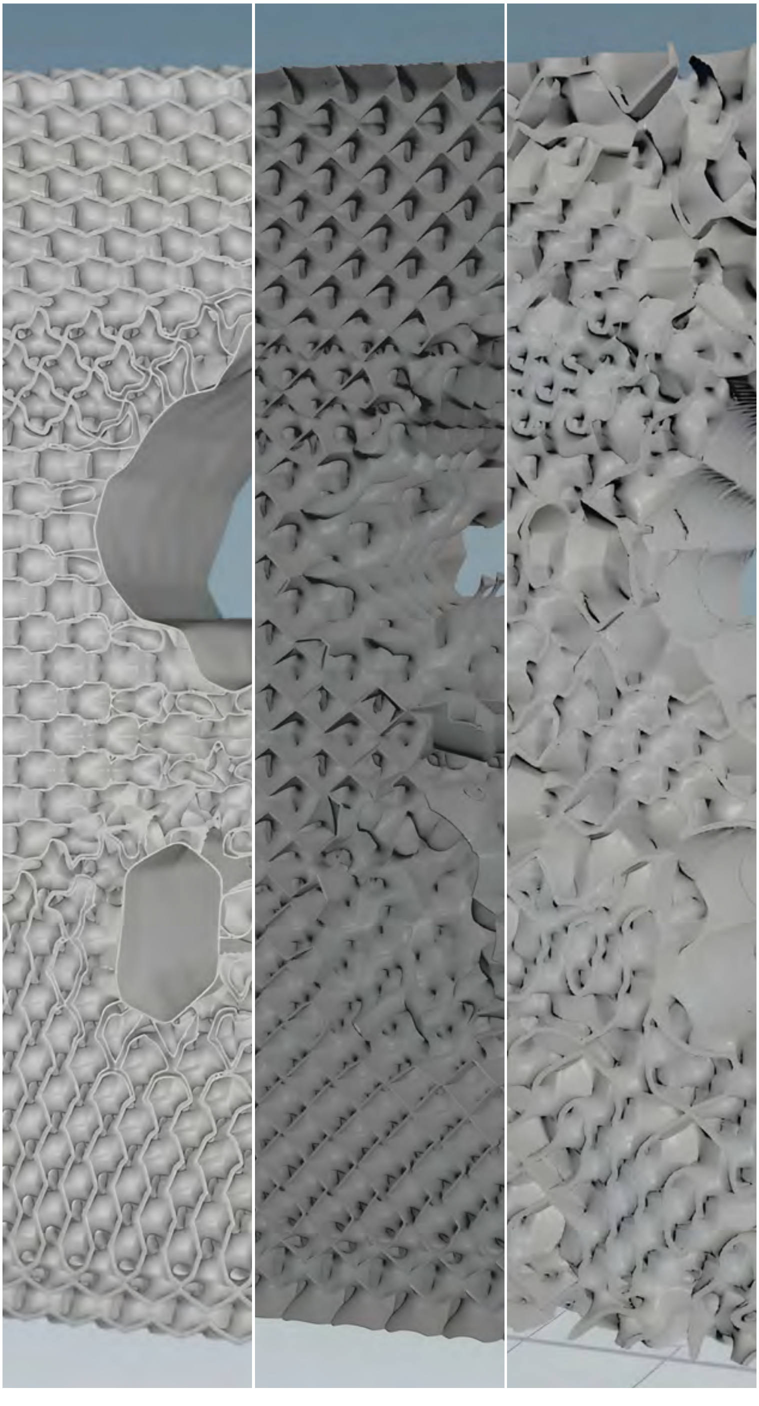






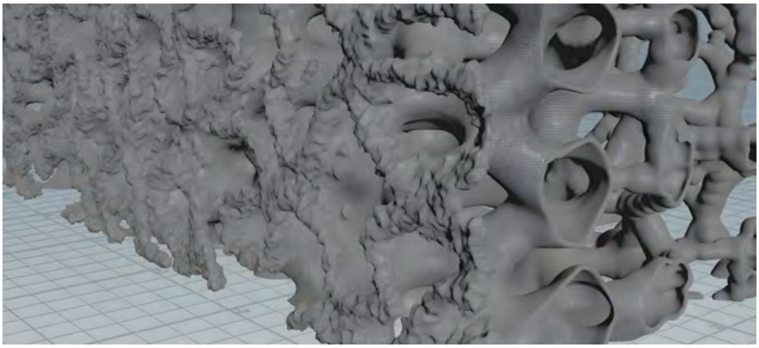
The three steps in the generation, as they were presented on the prototype: particle spring network, isosurface and voxel model. Here with the adjustments for production, shown in one of the components of the wall.

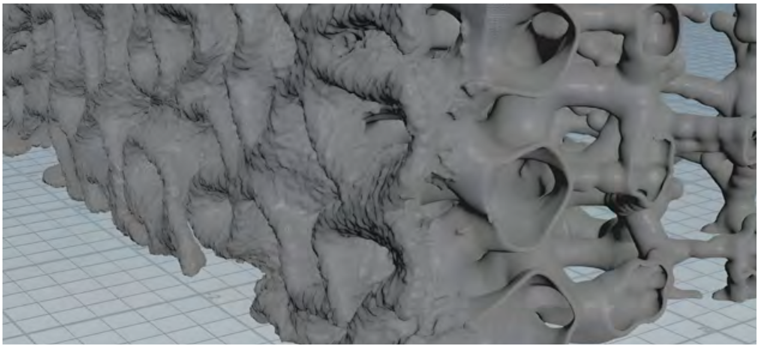
A few of the iterations of the exterior area. I integrated the windows into the base network, so that the channels are not disturbed by the openings. Also, the channels open into nests, represent the main aspect of the exterior. I introduced variation in their topology, so that larger nests can be created, for a wider range of microclimates intended for biodiversity.

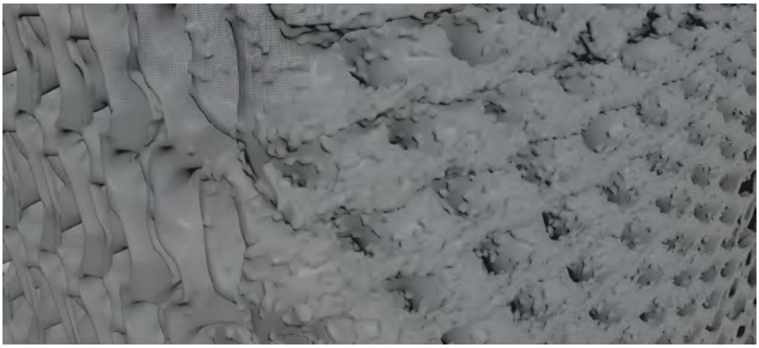


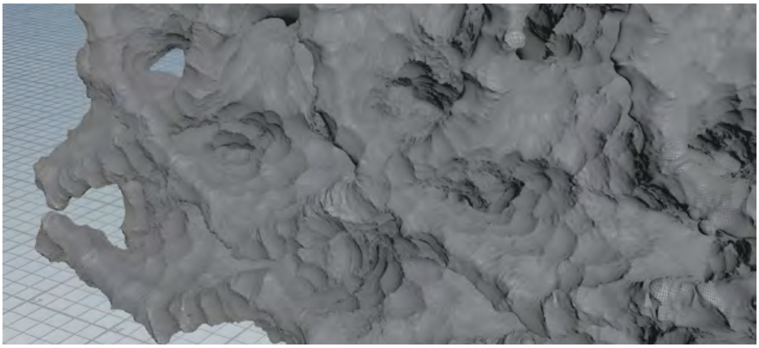
The air inlets have been tested and iterated, so that they would retain the same channel width as throughout the network, as well as for finding a solution for the textile attachment.

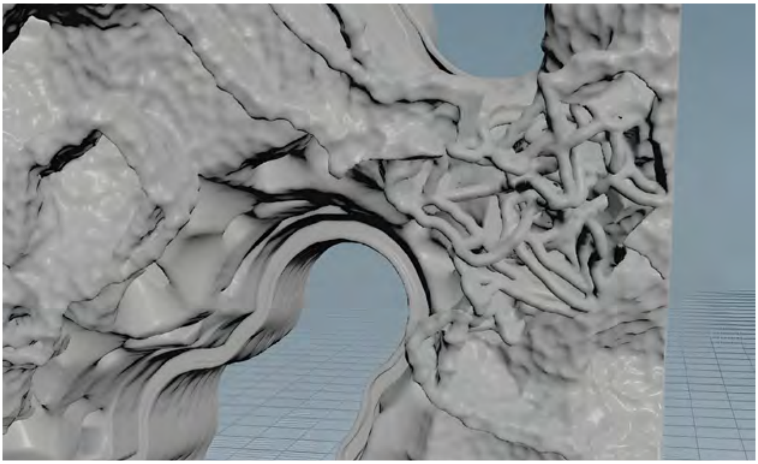
The exterior zone of the wall is intended to support a range of organisms that can increase biodiversity. For this reason, the design included surface rugosity, so that small particles can attach and accumulate over time. Different iterations were made, with the aim of achieving a design with a rough surface on the outermost end, and gradually smooth as it gets closer to the interior of the wall, so that there would be less growth inside. The images show the bioreceptivity iterations on the scale of surface rugosity.

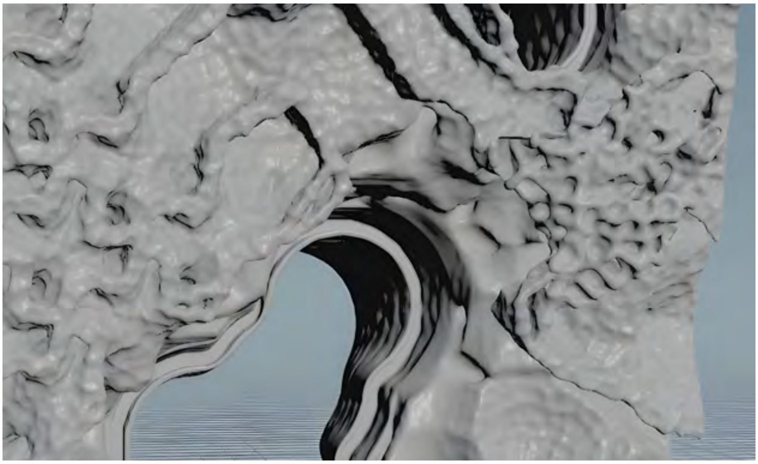


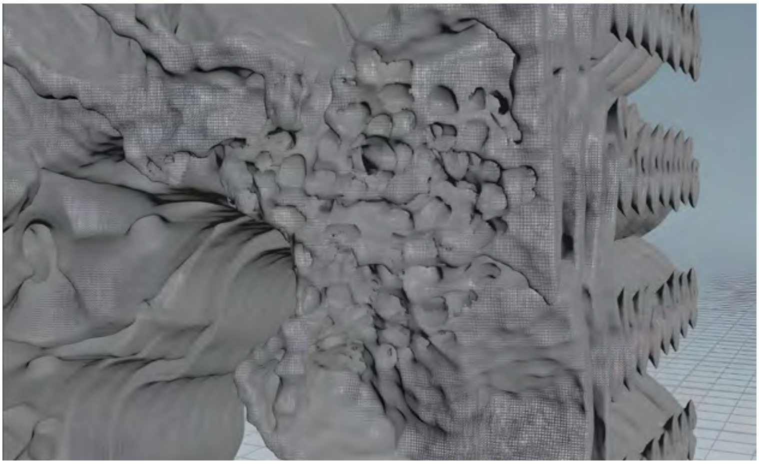












Another scale of design for bioreceptivity was focused on porosity pockets. These are perforated, allowing filamentous organisms, roots, and plants that need a stronger anchor to pass through it and attach. There have been several iterations in their design, aiming for perforations that reach beyond surface level, but that also do not result in strands that are too thin, and therefore risk being broken during fabrication, post-processing and assembly.

The printing was done by Voxeljet, on the VX4000 machine. All the components were produced in the same print job.

The first image is taken after the printing was completed, and the unpacking was underway. Part of the loose sand was removed.

The image below shows the de-sanding of one componen, using compressed air.

@ Voxeljet, 2021.

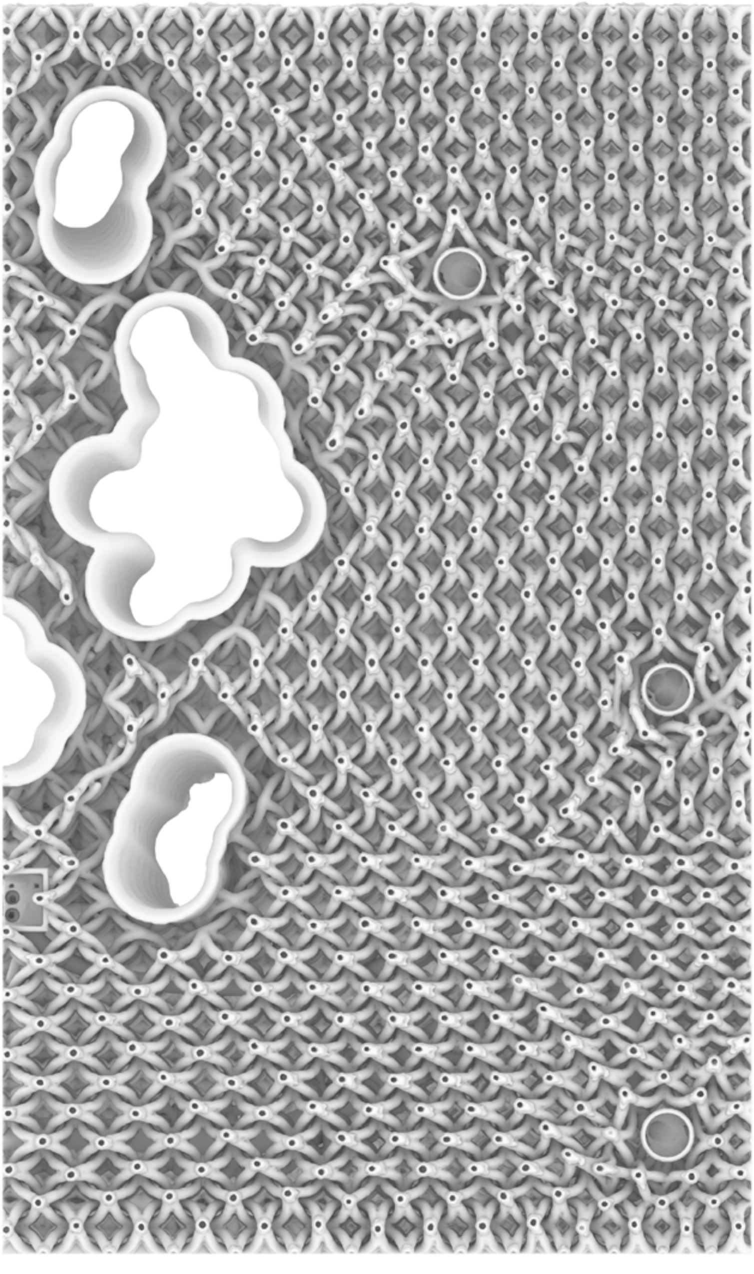
The 21 components, after unpacking and infiltration. The components were covered with another layer of resin, to ensure toughness and weather resistance. The infiltration was done by Sandhelden.

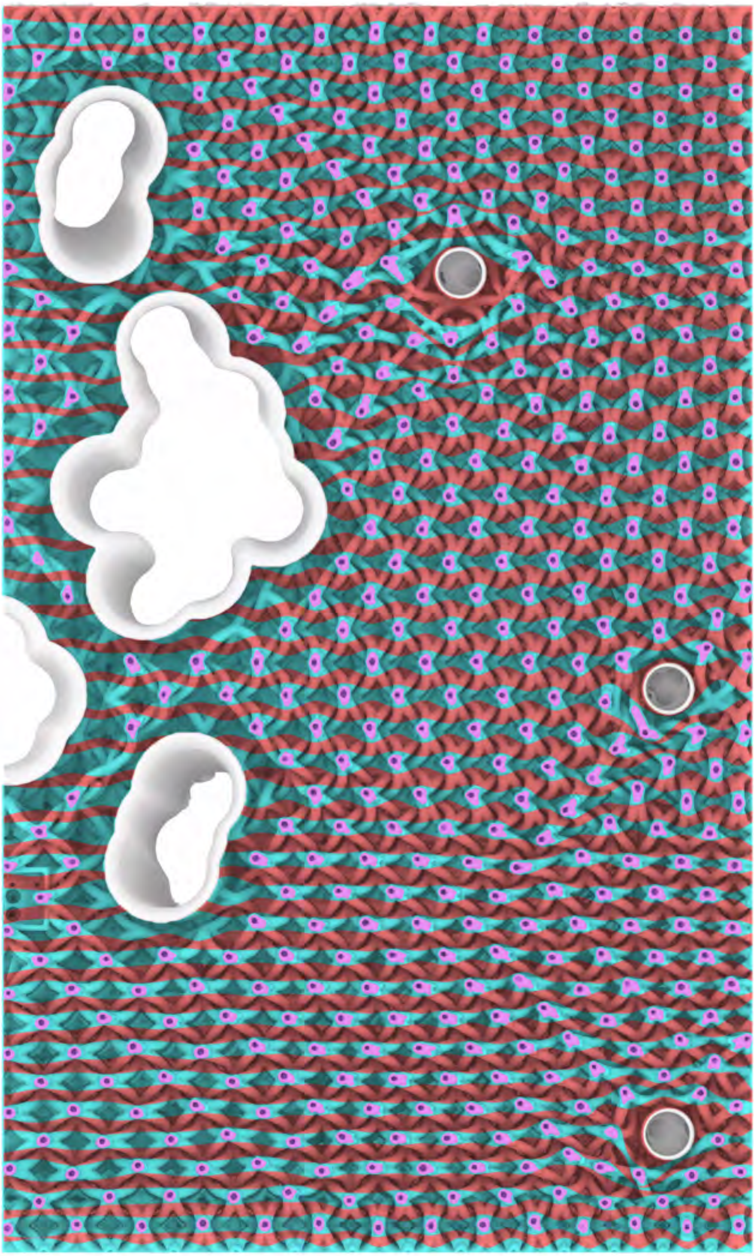
@ Sandhelden, 2021.

Detail of the air inlets, with the ridges for attaching the nylon inlay of the textile.

Detail of the bioreceptivity scales, in the printed component, and after post-processing: surface rugosity, porosity pockets, and some of the smaller niches on the exterior.

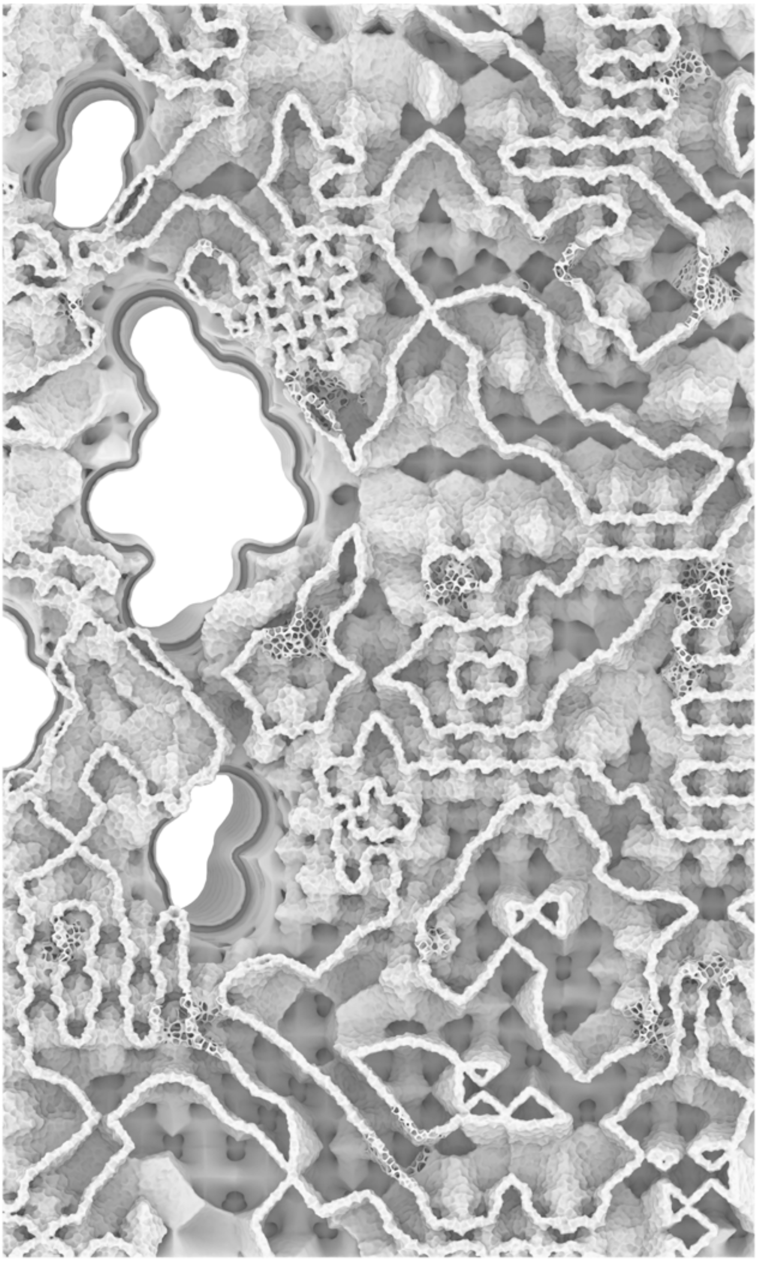
The interior volume of the wall was used to inform the interior textile regarding attachment points, windows, and openings for sockets.

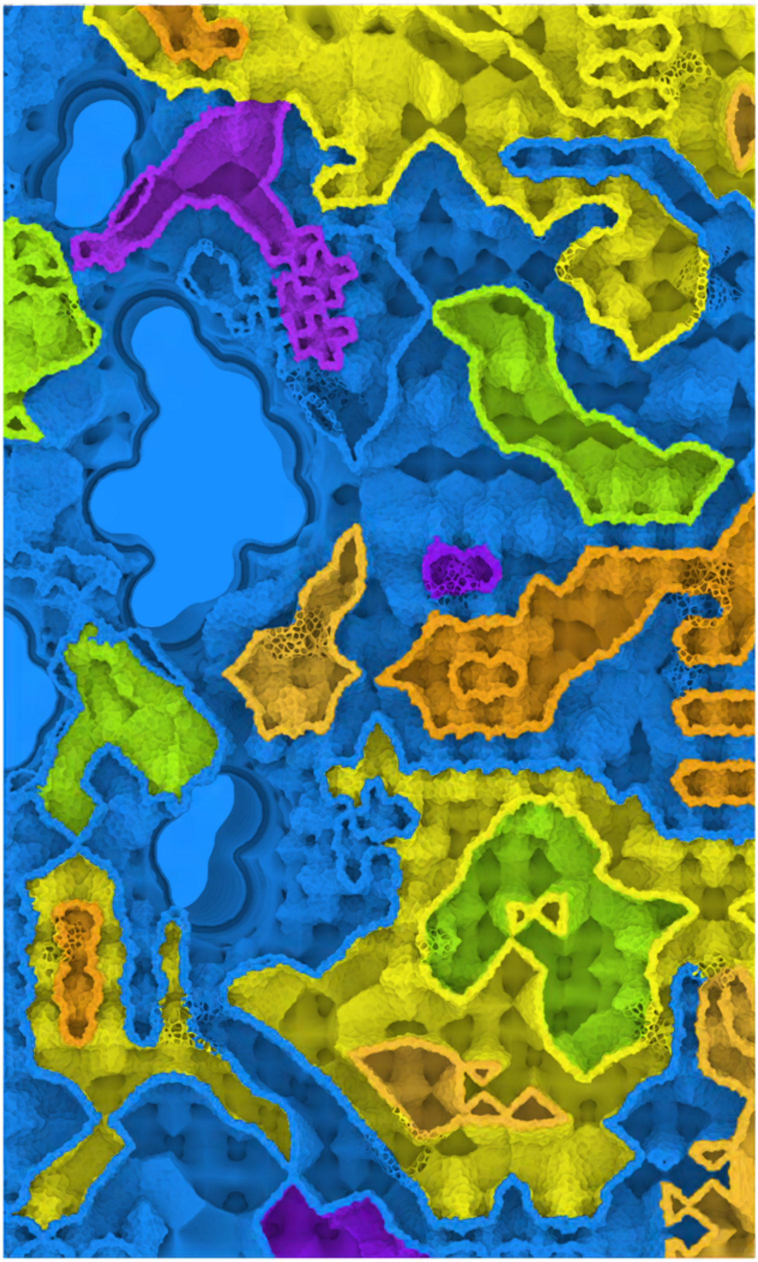




The interior geometry of the wall was the main driver of the patterns on the textile. This implied two patterns in the knit, distinct from the background. The first had a tight knit that functioned as a filter for the air exchange inlets. The second pattern was bracing the rows of air inlets on both sides. This pattern made the textile protrude outwards and included a continuous nylon inlay that was used for attaching and securing the textile to the wall.

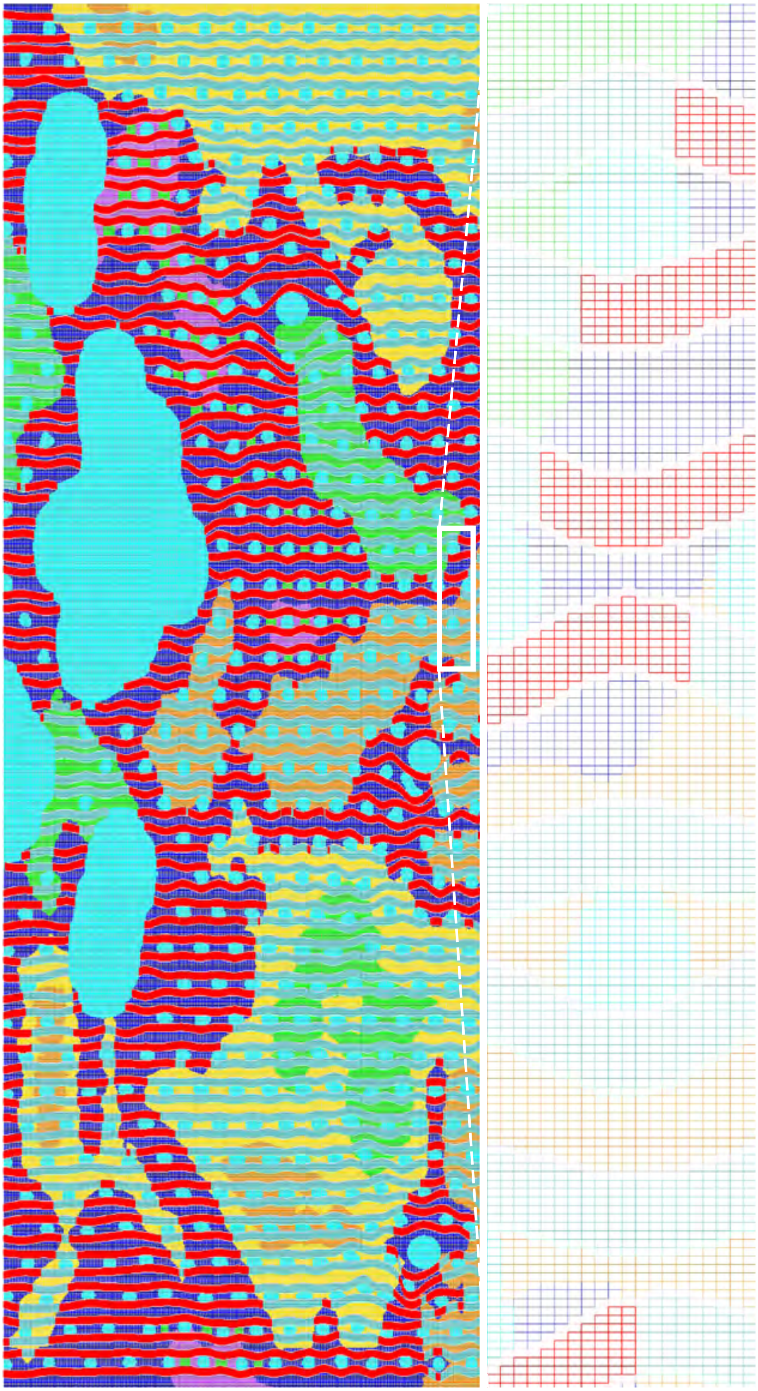
The exterior volume of the wall was used as the inspiration for generating the patterns on the interior textile.

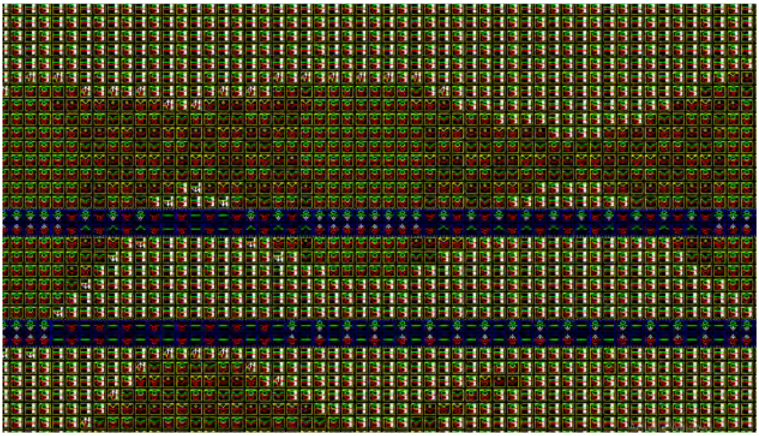




These outer wall zones were used to create inner zones on the textile. These corresponded to different CNC knit patterns. These were grouped by opening size and continuity, into 5 categories. They have different densities, so that parts of the wall are seen through the textile.

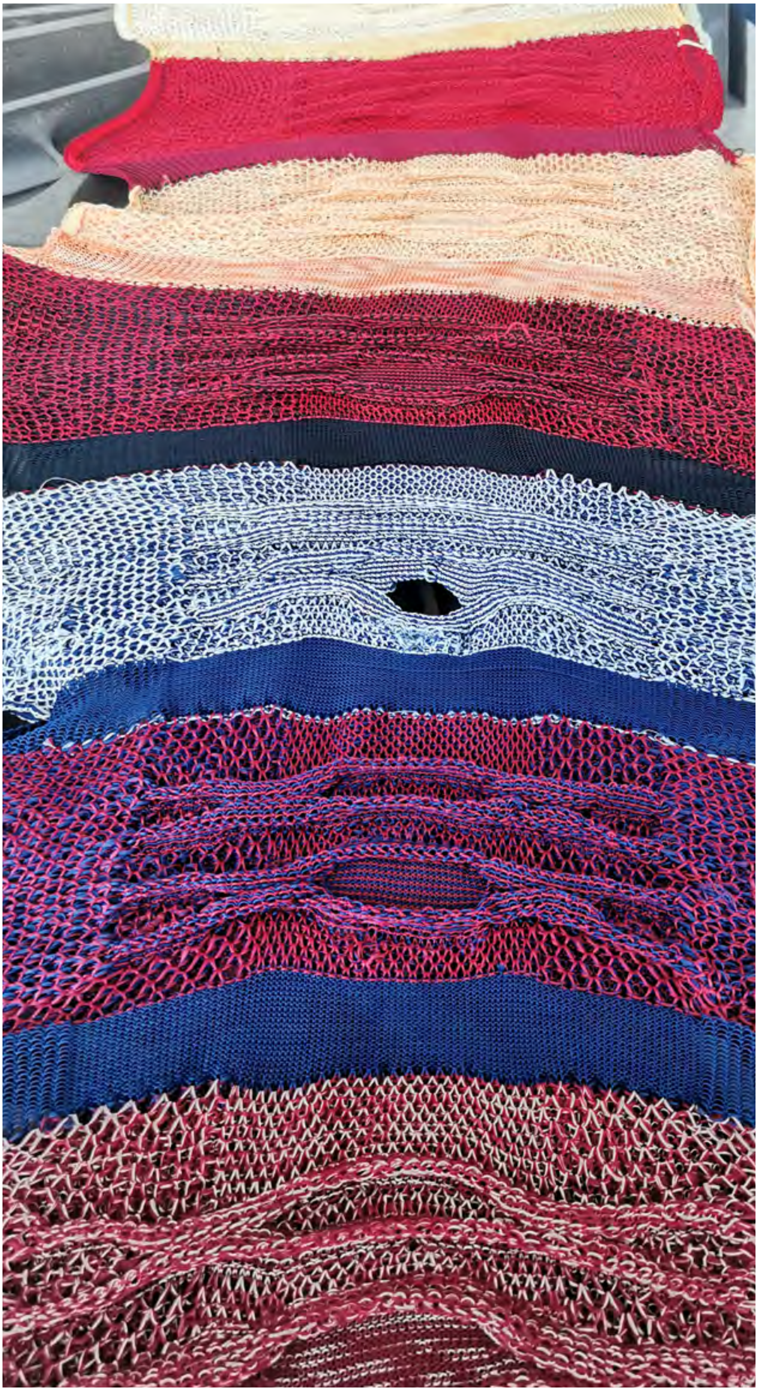
All the knit pattern zones from the inside and outside were combined into one file. This was then converted to a pixel grid, that was later used to generate the code for the CNC knitting machine. The individual pixels are seen on the second image

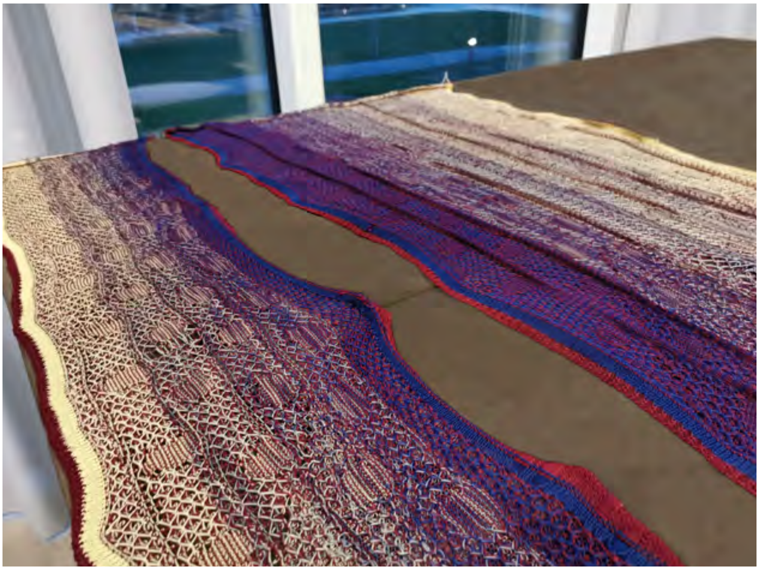




Each pixel was color coded to correspond to a machine operation that interpreted it and applied the desired knit pattern in that location. Here are visible some of the machine operations in their respective pixels, as they have been applied for the textile on the left page.
Below, detail with the nylon inlay pattern.

Textile probes testing color combinations. These also tested different types of ridges and patterns to be used throughout the textile.





The combination of colors and their gradient interference along the height of the piece.

Below is a close-up of the textile, showing the pattern on the inlet filter and two different densities of the knit pattern on the backdrop of the textile.

The interior textile was planned, tested and produced together with Mariana Popescu, at Block Research Group, ETH Zürich. The machine used for production was a 7 gauge Steiger Libra 1.130 flatbed knitting machine.

The result of the 3d CNC knit, that accounts for the curvature of the wall and ridge protrusion.

Packed membrane for assembly in Venice.

Photo by Mariana Popescu, 2021.

Installation of the textile on the assembled wall, at the exhibition site in Venice.

Photo by Mariana Popescu, 2021.

Components were packed in crates and arrived by boat to Venice, to the nearest dock close to Palazzo Bembo.

Even though it rained on the installation day, we assembled the wall in less than a work day.

The wall was secured at the base and cover with threaded rods.

6.1. Integrating transcalarity

Transcalarity played a central role in the design of this project, and this can be visible in the wall's bioreceptive outer section, intended to serve as an extended ecosystem. As previously discussed, ecosystems are examples of observed transcalarity. To foster a healthy ecosystem, it is important that the biodiversity aspect spans across multiple scales (McGlinn & Palmer 2019). The exterior of the wall opens up into a landscape of nests of different dimensions, shaped by the external outlets of the channels that aggregate into varied group sizes. This formation results in clusters with distinct sunlight exposure, depth, and protrusion, establishing diverse niches catering to a spectrum of species seeking their optimal habitat.

At smaller scales, individual openings present narrower niches of varied sizes, some standing alone and others clustering without merging together. The next level of bioreceptivity is a rugous texture applied in a gradient to the outside of the wall, intended to provide attachment points for roots and nutrient-rich particles. At even finer scales, tiny cavities with porosities and crevices capture water, offering shelter for an array of small organisms, from insects to fungi and algae. This overlapping scales of nests for bioreceptivity – in the overall geometry of *Meristem Wall* – is one way in which transcalarity takes place.

The wall encompasses functions that address different scales, some of which are entirely local in nature, and some which depend on global connectivity across the building as a whole. The space for the air turbulence to be activated, a phenomenon that takes place at millimeter scale, is defined through the network of channels in the computational model. While the demonstrator represents only a segment on a wall, it suggests continuity across the building scale through the particle spring network, which can connect and adapt to fit the piping and electrical networks throughout the whole building. Standard components such as doors and floor slabs can seamlessly be integrated with the wall system through the voxel model.

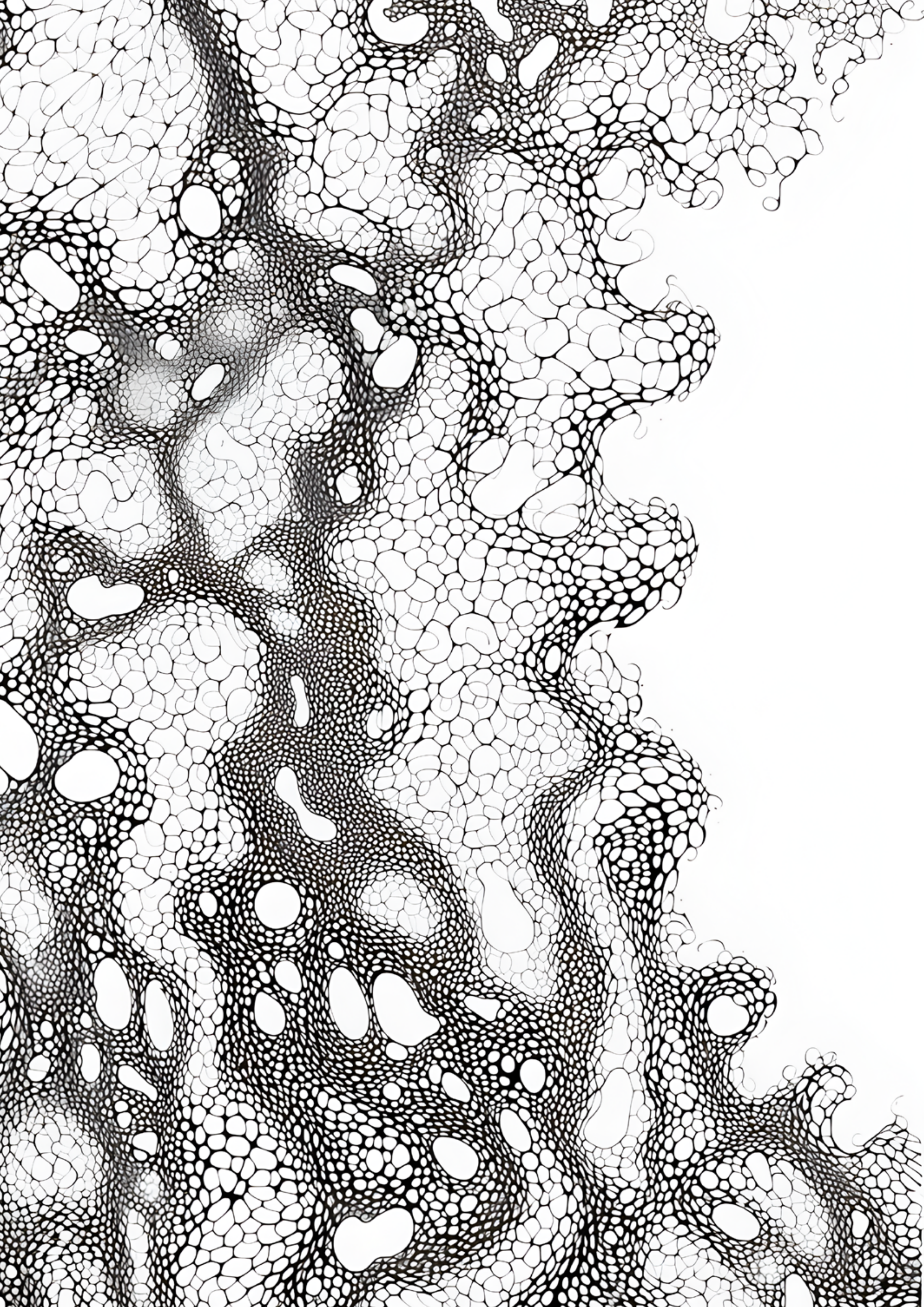
The wall's structural capabilities can be further fine-tuned to include loads ranging from building-wide loads to localized stresses. These can be calculated through FEM analysis and incorporated in voxel model through adding and removing ranges of voxels locally. Regarding the broader ecosystem, the design can factor in building data such as façade orientation and shading to cultivate an ever more diverse range of microclimates, tailoring the wall to its specific urban and geographic setting.

Each function operates within its own range of scales, and the computational model can operate to navigate and resolve conflicting needs and constraints. The volumetric model, through its potential for a multi-dimensional array of voxels, serves as a virtual environment for multiple algorithms and through which they can interact without being directly hardwired to each other. Changes made by one algorithm can be read and responded to by another algorithm, allowing for a high number of distinct functional agents (or algorithms), each operating at different scale ranges and with different performative and procedural logics. This mode of coordination is in biology (and sometimes computer science) described as “stigmergy” and is essential for the complex morphogenesis of biological structures. In this way, the voxel model could be understood as a form of stigmergy, facilitating indirect interactions among various algorithms.

An adaptive computational model has been used as the method to introduce transcalarity in the project. The set of algorithms has integrated functions that operate at different scales, and each scalar dependency has been formulated, expressed, and negotiated at the same time in the same model.

From the computational design point of view, this has some similarities with *multi-scale modeling*: nesting. However, *multi-scale modeling* provides a computational method to translate and move information from one level to another. As they state, this arises from the inherent limitation of a model that may lack the capability to identify issues internally. Consequently, for accurate testing of the implications, the geometry must transition to a different resolution level. Likewise, insights obtained at a lower resolution might necessitate adjustments at a higher one, which cannot be effectively evaluated using the parameters of preceding levels. Such complexities cannot be addressed by a linear model, as highlighted by Nicholas et al. (2016).

Following this, there are two points to be made in relation to these different methods. Firstly, *Meristem Wall* also employs three different computational models, that have different resolutions. The difference however is that these models are not nested within each other scale wise, they all encompass the entire span of the demonstrator, but provide information that is passed on to the next model to add resolution. And secondly, although from a strictly computational set-up this method is unidirectional, it has been employed multidirectionally, through iterative design. This means that as stated above, to test the implications of a model, information has been passed down to the next model, assessed, and then reiterated, several times, until information from each model has sufficiently spread to the others.



How can we know the dancer from the dance?

- William Butler Yeats, Among School Children, VIII

7. Swarm Materialization

This project explores the potentials of self-organized swarm construction to develop adaptive structures in low-energy materials. It investigates a process of construction that coincides with and continuously influences its own design, as is often the case in several nonhuman-built structures. Instead of viewing the design and construction stages as temporally and spatially distinct, this project blurs such linearities and separations, investigating how these phases might reciprocally inform each other and what the consequences for architectural processes may be.

The previously described design explorations have each probed the concept of transcalarity from different perspectives. Nonetheless, key aspects of transcalar interactions were not explored within the scope of these earlier projects. This design experiment explicitly develops some of these gaps in order to further the knowledge and understanding of design processes that incorporate transcalar interactions.

In complex emergent systems, transcalarity manifests through a tight scalar relation, with cross-scalar feedback loops. In *Pulp Faction*, these involved manual integration, through processes such as material tests and refinement through iteration. While in *Meristem Wall*, this occurred predominantly in a digital environment through sequential as well as parallel integration of algorithms.

Swarm Materialization sets out to integrate both micro-level phenomena like moisture migration, cracking, and distortion in material, and global or macro-level design outcomes. The proposed setup aims to establish a seamless connection across these scales through real-time feedback loops between the digital design environment and the physically manifested material artifact. Furthermore, this framework not only enables instantaneous adjustments in the design through its material feedback and vice versa, but also these adjustments accumulate over the time of construction and maintenance, adding a temporal dimension to the transcalar relations.

Acting as an experimental arena for examining two-way feedback from design to construction, this initiative is currently in an ongoing phase. Its integration in this dissertation is therefore of a partly speculative nature. Even if not a fully executed project, it has materialized through a prototype aimed at assessing different elements of the setup. Through its conception, I attempt to delve into a different type of process for design and fabrication which integrates biological design in its multi-agent, continuous, decentralized, and dynamic process. In this way it extends the discussion of transcalarity beyond the scope of the first two design experiments.

7.2. Stigmergy in construction

Stigmergy, defined by Grassé in 1959, was first observed in the behavior of Macrotermes termites as a strategy employed in their mound construction. It serves as an essential system for task coordination and regulation. It functions through environmental cues: an agent perceives a stimulus in the environment and reacts by altering that environment in some way. This change, in turn, triggers a new, similar or different, stimulus for another agent, creating a ripple effect, until these cumulative interactions, lead to the emergence of self-organized, intricate structures.

In nature there are many examples of collective construction driven by swarm intelligence. Each of these examples demonstrates unique approaches to structure, scale, and materiality. The types of interaction between the agents in a system are dependent on the size of the collective and its structural complexity. However, they generally all rely on stochastic planning, decentralized execution, and local sensing, where the environment influences through positive and negative feedback, and homeostasis the development of the structure growth (Petersen et al., 2019).

Notable examples beyond termites include Oecophylla smaragdina, or weaver ants, who construct their nests in tree foliage by weaving leaves with silk produced by their larvae (Sangma & Prasad, 2021). Similarly, Philetairus socius, also known as sociable weavers, build nests from dry grass and twigs that can last decades and span several meters across (Collias & Collias, 1978).

Drawing from these biological inspirations, the project seeks to extrapolate and apply the principles of stigmergy to create a process for adaptive, nonlinear construction. Through stigmergy, swarm systems enable swarm constructors, such as termites, to collaborate and build complex structures without any centralized blueprint or top-down control. Local cues facilitate interaction and multi-objective optimization of structures in natural construction (Petersen et al., 2019).

Incorporating stigmergic principles into human architectural and construction processes requires a reimagining of conventional construction practices, which often rely on predetermined blueprints and fabrication separated from design. But by leveraging principles of self-organization, adaptability, and decentralized coordination found in natural swarm systems into human construction, new paradigms in building processes could emerge.

Such approaches would not only offer inherent flexibility, but they also have the potential for increased sustainability and resilience. This is particularly valuable in today’s built environment, as these methodologies would enable the use of locally-sourced, and weaker materials that could be continually maintained and adapted over time.

7.3. Distributed fabrication

This chapter outlines the current state of research in agent-based construction and related areas that are the foundation of *Swarm Materialization*. It is an emergent field, that intersects multiple research areas: agent-based simulations, distributed robotics, discrete fabrication, especially involving earth-based materials, and live-sensing feedback systems in design processes. This section also underscores how the project contributes to the growing field by addressing certain gaps.

Agent based construction processes in biology rely on the coordination of large swarms of individual organisms (agents) that collectively shape their environment through different behavioral algorithms. These agents are vastly more complex than any machine that can currently be crated through engineering, which poses a significant challenge in trying to mimic these processes for architecture and construction. Because of this, current and past research in the area tends to fall in one of two distinct approaches: agent-based simulations that experiment with behavioral algorithms in order to construct spatially complex virtual environments, and swarm robotics where the emphasis falls on developing robots that can sense and manipulate their environment and operate in swarms. The former approach is limited in terms of the material environment, as the simulation represents a simplified version of real materiality. The latter is capable of interacting with a complex material world, but with more restricted behavioral algorithms and with higher limitations of robotics when compared to biological organisms. In order to overcome these limitations, this project seeks to explore a hybrid approach, which combines virtual and material environments through discrete deposition technology.

7.3.1. Agent-based simulations

The principles of agent-based simulations operate on the notion of emergence. In these simulations, the focus is on how individual agents, acting based on a set of predetermined, often simple rules, interact with each other and their environment. The actions made are based on local sensing and decision making at the scale of the individual agent. These interactions often result in complex structures that are not directly programmed but emerge naturally from the bottom-up collective behaviors of the agents.

These agent-based systems have been studied in various biological phenomena. Although a large body of work is in insect colonies, they are also found and have been examined in flocks of birds, herds of animals, bacterial colonies, or neural networks (Yamins, 2005). Such biological systems provide insights for informing multi-agent simulations. More specifically, swarm simulations have integrated the capacity of learning from social insects through their environment, offering pathways to replicate complex behaviors in computationally (Miranda & Coates, 2000). The field of swarm simulations provides the theoretical foundation for further exploration in *Swarm Materialization* project.

7.3.2. Distributed Robotics

Often referred to as Collective Robotic Construction (CRC), distributed robotics in construction it is an area of research focused on construction through autonomous multirobot systems. These have the advantage of covering a much larger volume than the size or reach of individual robots (Petersen et al., 2019), and are intended to integrate the local, stigmergic interaction that manifests through emergent designs, incorporated in the robot-to-robot interaction.

However, implementing these robotic systems in dynamic environments presents a set of challenges. For instance, planning the interaction, coordination between robots and path formation involves complexities that have so far limited real-world, large-scale applications. In CRC, the goals can either be defined by fixed blueprints or by more adaptable specifications. Existing approaches often resorted to centralization and predetermined geometries to simplify computation. One example is the aerial footbridge built by quadcopters at ETH as a tensile structure with knotted, continuous fibers. With a span of more than 7 meters, it involved coordination between several drones. However, it relies on a centralized control system that provides the location and altitude of the drones (Mirjan et al., 2013). Their path is pre-planned, and the motion control system allows for path correction (Augugliaro & D'Andrea, 2015).

The *Termes* project serves as a case study for decentralized robotic systems inspired by termites (Werfel et al., 2014). The robots in the *Termes* project are designed for stacking brick-like elements. Additionally, they possess the ability to climb to access to multiple deposition sites. Although the system is provided with a predetermined geometry outcome, the series of actions necessary for its realization are determined in a bottom-up fashion. These robots are equipped with local sensing capabilities and communicate indirectly with one another, through stigmergic interactions with their shared environment. This creates a system where decision-making is decentralized, and therefore more scalable - since there is no centralized data handling system that could potentially get overloaded — and resilient, as it does not rely on a single point in the system, which could fail (Werfel et al., 2014).

Importantly, all the robots operated under the same set of rules and did not preplan their actions. Instead, they reacted to the circumstances. This leads to complexities in terms of sequence and timing, which were part of the specific challenges in the project. The inherent parallelism of this swarm system, with a wide range of possible paths, amplifies its strength and resilience (Werfel et al., 2014). The decentralized nature of this project underscores both the promise and the obstacles of CRC, particularly the trade-offs between adaptability and resulting structure complexity.

Fig. 16. Remote Material Deposition Installation, Sitterwerk, St.Gallen, 2014. Source: © Gramazio Kohler Research, ETH Zurich.

7.3.3. Discrete deposition

The area of discrete deposition, as framed in this study, refers to projects that develop on the principle of depositing material in a sequential manner.

Previous research, such as the project by Dierichs & Menges, has highlighted the potential of fabrication with discrete elements in *aggregate architecture*, allowing for self-organisation and continuous reconfiguration (2012). *Swarm Materialization* proposes an aggregate material system that sits between discrete elements and layered fabrication.

A project that holds similarities here is the work by Ming et al. (2022) in *Impact Printing*. This project employs robotic deposition of soft discrete elements, relying on the impact of deposition forces to enhance bonding between depositions. The method employs a nonlinear order of deposition, similar to *Swarm Materialization*. However, where they diverge is in the focus on remote deposition in the former.

Another project that offers a closer parallel is *Remote Material Deposition* by Dörfler et al. (2014). In this work discrete loam masses are placed at a distance from the robotic system, again utilizing a nonlinear, material-driven fabrication process. One aspect of this project that is similar to *Swarm Materialization* is its incorporation of sensing and feedback systems, allowing the design to dynamically adapt to the real-world conditions of the fabrication process. As the material behavior from the impact of the projectiles is too complex to be fully simulated, the project includes a digitally sensing system that feeds back into the model, updating it. This then corrects to deformations and uncertainties that arise from the dynamics of the process, the material, or the construction environment. This bypasses the need for simulating complex material interactions, and therefore the need for material abstractions. The results are in distributed form-finding, even of not at global design level, but at material aggregation and mid-scale levels (Dörfler et al., 2014).

A more recent project, *Clay Rotunda* (2021), had a similar manufacturing process to *Swarm Materialization*, as the deposition was not remote, but directly placed by the nozzle onto previous depositions. It concluded in the construction of a free-standing thin-walled cylindrical structure for sound-proofing. Since it is not deposited through impact, the bonding between the depositions was of high importance, and this was ensured through the orientation of the placement of the "soft bricks" and segments (Clay Rotunda, 2021). This project also incorporated 3d scanning during the fabrication process.

Fig. 17. Clay Rotunda, inner wall detail, SE MusicLab, Bern, 2020-2021. Source: Photo: Michael Lyrenmann. © Gramazio Kohler Research, ETH Zurich.

7.3.4. Live sensing and feedback-driven design

The introduction of live-sensing technologies and feedback loops into the design process offers a new trajectory to traditional design methodologies. *Robosense* (Bilotti et al., 2018) employed real-time sensing for the live introduction of design adjustments. However, unlike *Swarm Materialization*, these design interventions relied on designer control rather than leveraging the intrinsic properties of materials for real-time adjustments.

Swarm Materialization departs from these precedents in the intent to employ live data to dynamically update both the design objectives and the fabrication process. This methodology contrasts to traditional workflows, where design largely precedes fabrication. In *Swarm Materialization*, the design objectives are not entirely predefined but evolve based on the emergent behaviors of the system, driven in part by the material properties themselves. It aims not just for error correction, but also for a fluidity of design goals, enabled by the complex, nonlinear behaviors of earth-based materials. While it may not offer the extended physical reach possible through distributed robotics, it enables a new level of complexity and adaptability by integrating live sensing and agent-based simulations.

7.4. Methods

The solution proposed here for incorporating stigmergy into construction is through a hybrid approach that combines Liquid Deposition Modelling (LDM) extrusion 3d printing of clay, with virtual simulations of swarm behavior. This method enables two-way feedback between the physical and virtual environments, allowing the construction process to evolve continually in response to the ongoing simulation. The robotic deposition of clay takes place in a discontinuous (discrete) and nonsequential manner (Andréen et al., 2019), while the materialized structure is recorded through various sensors, primarily 3d scanning - but it could be additionally recorded through RGB machine vision and other sensors, such as moisture, temperature or pressure.

In parallel with the physical fabrication, the design decisions are constantly negotiated in a virtual simulation of a multi-agent swarm, whose actions determine the next robotic depositions. These decisions are informed both by a behavioral goal inherent to the swarm algorithm(s) that guides the form-finding, as well as by the live information fed by the sensors from the fabricated geometry. In this way the design is based on real information and can be adaptive, not only to correct the print path, but to alter the final global design. The behavior and actions of the agents that result in material deposition are based on fully local goals, and do not aim to fabricate a pre-determined geometry as is the case in *Termes* project (Werfel et al., 2014).

7.4.1. Computational design

This section describes the proposed computational design setup. *Swarm Materialization* relies on a multi-agent system, reacting to the swarm behavior, as well as input from the fabrication to generate the design. Within the swarm there are several types of agents, each programmed with distinct objectives and triggers. These are compared with the types of complexities found in termite mounds.

In the termite mound, the behavioral patterns of these builders are initiated and influenced by a range of environmental conditions, such as humidity levels, temperature, or physical constraints. Furthermore, the environment itself isn't static, but it continually changes, influenced by the actions of other agents within the swarm and the weathering or passing of seasons. Here, different agents have different ways to respond to specific environmental conditions. For example, if a drop in humidity is detected, 95% of agents might have a subroutine to move away from that area, while the remaining 5% might perform a different, specific action. They can then also recruit other termites to perform specific tasks, either through direct interaction or indirect means such as stigmergy. This introduces a probabilistic distribution into the response of the swarm to any given condition, enhancing the complexity and adaptability of the system.

Therefore, the agents in this computational design setup are not intended to be modeled after individual termites, but are rather types or classes that contain a variety of subroutines, according to this probabilistic response distribution. In this multi-agent system, stigmergy is not just a communication protocol but also a method for optimizing conflicting objectives. For each functional goal, such as ensuring structural stability, maximizing surface area for material drying, or facilitating airflow, there is a type of agent or group of agents responsible for its enforcement. Some agents might prioritize height, while others would be programmed to focus on filling out a predetermined volume or blocking the depositions that would become obstacles that would then hamper the following deposition process.

7.4.2. Printing

The fabrication of the prototypes was done with an ABB IRB2400 robot arm, equipped with a Lutum Vormvrij extruder. COMPAS RRC handles the toolpath information which is calculated for each extrusion based on the current geometry as recorded by the scanner, feeding it to the ABB IRC5 controller that directed the robot arm.

In the prototype set-up, the material is stoneware clay, and it was mixed with approximately 20% water wt to a suitable consistency. The clay was extruded through a nozzle with a diameter of 7 mm.

The high viscosity and plasticity of the material combined with its reversible setting process based on drying is what allows for deformations to take place during fabrication. In a conventionally separated design-fabrication process such deformations are a problem, but in a dynamic process as described here, it results in potential for material self-organization and adaptive fabrication. As the printing is done with wet clay, the self-cohesion of the wet material depositions are enough for bonding, as observed by Ming et al., (2022). This technique also allows for printing onto uncontrolled surfaces, due to the adaptive nature of both the material, as well as the fabrication system, that incorporates scanning and response. Similar to *Impact Printing*, it can produce a construction method that sits between a discrete building blocks additive deposition, such as brick laying, and extrusion based 3d printing of solidifying material (Ming et al., 2022).

7.4.3. Sensing

The fabrication setup includes a stereometric camera, which is configured to continuously scan the geometry of the extruded clay, and is intended to update the “digital twin“ which serves as the environment for the agent model after each extrusion. The data collected is in the form of a point cloud, which is transferred to a volumetric model where the agent algorithms operate.

The camera is mounted on the robot instead of on a fixed point external to the robotic system so that it can take 3d information on the entire printed structure, including interstices and places that would be hidden beyond a singular-source ray-point perspective.

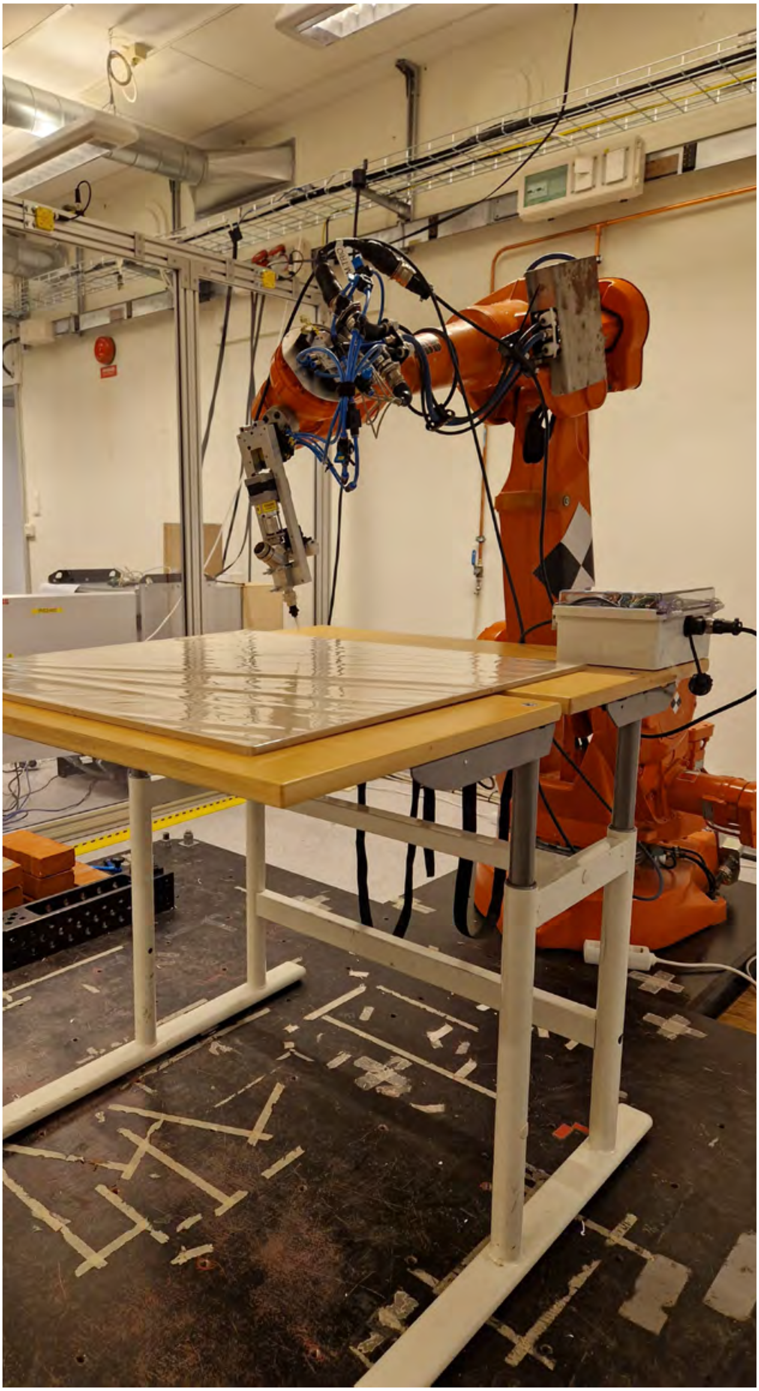
There is a potential for this setup to work with several other types of materials, ideally malleable, with corresponding adjustments. These could be employed for example for a cellulose based material, or fungal biocomposites. Besides 3d scanning, the type of sensed information would need to be supplemented with data corresponding to the needs of the material, for example in the case of fungal materials, humidity and temperature. This data could be collected either though a sensor probe, or potentially through visual data – in RBG format for wetness and in IR format for temperature.

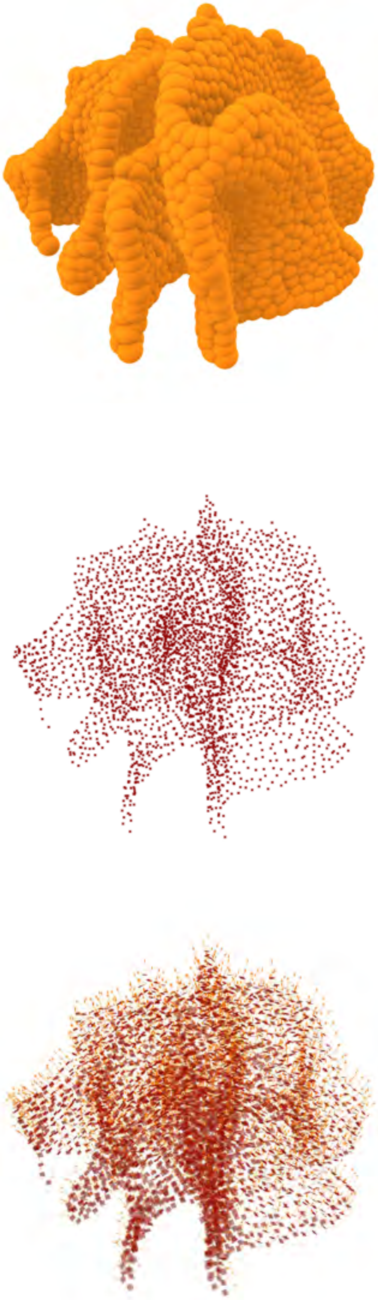
7.5. Visual journal

The journal of this project is brief, showing the setup and one prototyping session.

The material used for extrusion is stoneware clay. However, it is expected that several types of clay are suitable. The intention is that by supplementing with the necessary additives, local soil can be employed.

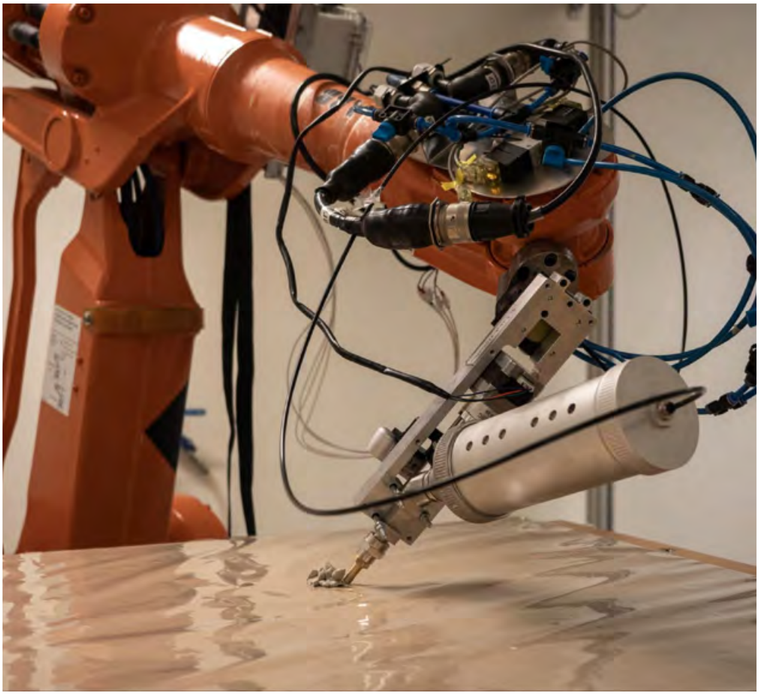
Fabrication setup: ABB IRB2400 robot arm, Lutum Vormvrij extruder connected to compressed air outlet, stereometric camera.

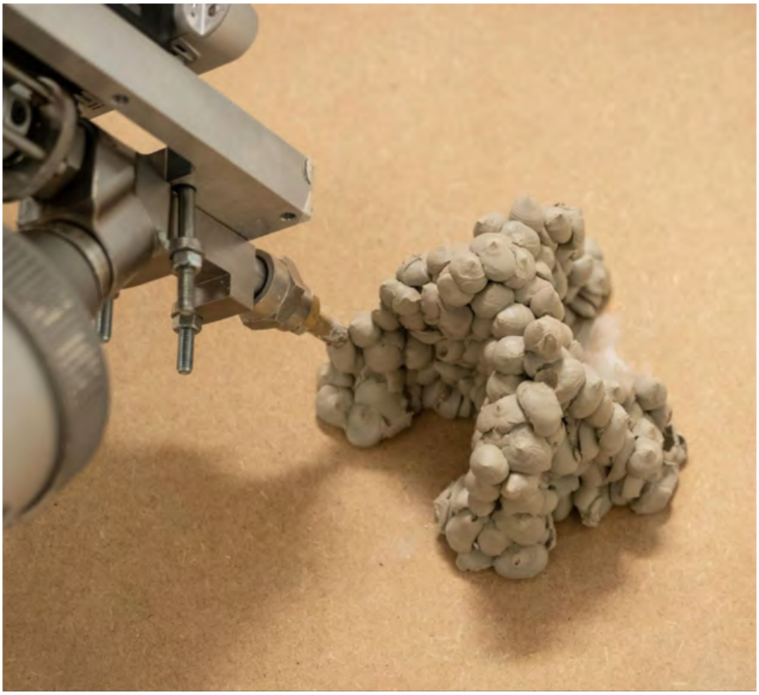




The initial prototype, with the simulated globs on the top, their centerpoints as print targets in the middle, and the extrusion direction on the bottom.

The first prototype of Swarm Materialization tested the adhesion between the globs, the angle of the deposition, and the fabrication set-up in general. Bottom shows the print consisting of 400 globs.





7.1. Integrating transcalarity

Swarm Materialization proposes an arena that seeks to overcome the limitations of previous design experiments by following biological morphogenesis through enabling a two-way feedback between process elements in multiple scales, spatial as well as temporal.

As the design is entirely generated by an agent system in real time, along with the processes of construction and living, there are very few top-down requirements directly imposed at any scale. However, different types of agents have different objectives, and through the continuous feedback between the design intent and evaluation of the fabricated output, the resulting design contains specificity at several scales of resolution.

Stigmergy is a design principle that specifically addresses the discrepancies of scale between the agents that operate locally and the performative, functional needs that often exist at a global scale (e.g. that of the mound, the colony, the body, the building, or the city). As an agent makes an adjustment at the local scale, the effects cascade through the system, influencing both other agents and carriers of function at larger scales, such as air flow, gas and moisture concentrations and load propagation. As multiple agents operate in parallel, there is no definitive hierarchy imposed, and scalar interactions take place in multiple directions. In contrast to an analytical optimization, this process is perhaps better understood as a negotiated structure.

Conventional architectural design is primarily articulated at the scale of human spatial perception and above, such as visible in detailing, rooms and building-level design or infrastructure morphologies. The smaller scales within this domain are usually standardized and prepackaged, and the design process may include picking from a catalogue of prefabricated or pre-conceptualised parts. This reflects the current building industry practice: separating processes into clearly defined and separated phases, in a hierarchical manner.

Here, in *Swarm Materialization*, the design is instead strongly influenced by the smaller scales, in a bottom-up manner. The two scales are deeply interlinked – local action and the global form. The scales in between emerge from, and hence are dynamically defined by these extremes.

To an extent, the same principle is applied in *Meristem Wall*, even though there are considerable top-down influences in the global geometry and the material is standardized. The stigmergic marker or environment in this earlier project is simulated in the volumetric model and sits at a particular sequential slot in between more conventional, top-down design processes and an irreversible fabrication. The approach of *Swarm Materialization* allows for real material computation, and does not have the requirement of a "design freeze" in the fabrication stage.

This is also true in *Pulp Faction*, but concerning instead the materiality, which has a customized composition to fit the fabrication and living agents of the material.

A transcalar effect here is seen in the relationship between local sensing and action of individual agents, and their cumulative behaviors leading to the emergence of global geometries that perform effectively with respect to their conditions.

The aim of the project was to set up an experimental arena for closing the loop between the generative digital design and materialization. This is why the set up is focused in two areas: the digital computation, where the initial generative design takes place. This is also the place where new data is taken back in and integrated to update the future design generations.

The second aspect is the materialization, where the clay is extruded in globs and deposited successively. This project does not have specific geometries to be fabricated through 3d printing; from the material point of view, it has the opposite strategy as *Meristem Wall*. Instead, although there are general goals inscribed in the agent behavior, the geometry is intended to emerge bottom up, from agent interactions and importantly, from material performance. In this way, instead of being abstracted to a set of properties, the material is directly recorded, and its behavior is integrated as a live parameter in the design process. The exact geometry of the globs, the shape they take after shrinking when the water evaporates, the appearance of any cracks, whether any globs become displaced or the position they take when squeezed by the neighbors, these are taken as specific events that have a direct impact on the trajectory of the design through transcalarity.

Instead of assuming a passive materiality, *Swarm Materialization* starts from the premise that material is so active, that its agency as it particularly occurs in each fabricated instance, is an integral part of the design process. This approach opens avenues for the introduction of nonlinear materials into construction. These nonlinear materials are often the non-industrialized and difficult to predict through traditional computational simulations, and therefore have been mostly removed from the industry – even though they hold high potential due to their local availability.

Typically, the automation of machine produced parts and components is resulting in a sought-after identical result, iteration after iteration. Here however, through the integration of input from the material behavior, together with the inherent unpredictability of clay, different results would occur in every iteration. These locally available materials have not been introduced to a wider extent in contemporary architecture, and one of the reasons is the lack of standardization and predictability, when compared to industrialized materials. Another reason is the weathering of the material. Since it is not waterproof by itself, it requires to be either combined with other materials to withstand rain, or be included in a maintenance system of the building.

All of existence involves continuous trans-scalar encounter.

- Zachary Horton

8. Discussion and conclusion

This section will begin by directly addressing the research questions and the answers that have emerged, followed by a statement of the main discoveries of the dissertation. Furthermore, the discussion extends to the relationship between biodesign and sustainability. In conclusion, the insights and reflections gathered from these findings are synthesized.

8.2. Research questions

How can biological principles be integrated into architecture through computational design and additive manufacturing?

The introduction of biological principles into architectural practices offers a potential to incorporate the variation, adaptation, efficiency and resilience found in nature. In this dissertation, through three design experiments, it was shown how computational design and additive manufacturing can serve as channels for this biological integration.

In the realm of biological design, there exists a complex interplay between function, process, and geometry where one cannot be fully separated from the other. In conventional architectural design, these aspects are often isolated and treated separately. However, through the framework of transcalarity, additive fabrication allows the formulation of a computational framework centered on relational dynamics and process-oriented design, as opposed to composition through separated, predefined forms.

When the fabrication process incorporates living biological materials, the agency of materials becomes even more essential to be integrated into the design process. This implies that the task becomes to design both for the human end user and for the biological organism.

Using tools capable of addressing transcalar relationships, biological logic can be more deeply integrated into architectural design. These tools need to engage with the interconnectedness of various design targets across multiple spatial and temporal scales, which is important for optimizing performance within resource constraints. Computational design facilitates the integration of these transcalar principles by enabling complex systems characterized by multi-directional feedback loops. Digital fabrication technologies become crucial when realizing the complex geometries that arise from this multi-scalar interplay.

A core feature of biological systems is the emphasis on local agency. This ability of individual components to act complementary to a centralized, top-down directive can enrich architectural design practices, among others through the implementation of computational models based on generative systems. Such systems enable transcalar design paradigms where global performance emerges from localized interactions, and in varying ways they have here been present in each of the three projects. In *Pulp Faction*, the toolpath generation was tailored to meet structural requirements at column level through an algorithm that acted locally on the input of an approximate desired geometry, and transformed it based on the local perspective around the nozzle and the previously deposited material. The parameters were adjusted based on both the fungal biology and the rheological properties of the extruded pulp. In *Meristem Wall*, elements with specific “agendas” or functions operated independently but were integrated at a higher level. This level of interaction was both direct, as in the different sets of forces in the particle-spring system, or indirect, through the voxel model. Similar to *Meristem Wall*, but emphasized as a central topic in the investigation, *Swarm Materialization* also utilizes principles of stigmergy, but takes it a step further by proposing to impart materiality to these computational stigmergic markers in the physical world, which are then read by virtual agents. By taking the material computation into the physical realm instead of relying on simulation, it can include a wide range of complex material behavior, that are thus integrated in the system. A greater level of complexity in material computation can be tested through feedback between the material output and the digital environment.

How may transcalar effects be identified and used in design processes, material systems, and fabrication methods?

The concept of transcalarity involves the consideration of different scales, both temporal and spatial, within a system. It is particularly relevant in complex systems such as those encountered in biological design, as generally, the complexity of requirements, constraints and factors that are present in architectural practice can benefit from transcalar integration. One crucial feature of transcalar effects is their emergent nature — these phenomena are not easily predictable and must be learned and coordinated in each new design context.

This necessitates a methodology that allows for iterative learning and adaptation. To this end, the research by design framework has been particularly relevant, as it combines physical prototyping and experimental setup with computational simulations. This approach facilitates an in-depth understanding of transcalar effects, starting from the stage of conceptualization to testing, implementation and scaling up. Furthermore, the demonstrators of *Pulp Faction* and *Meristem Wall* have proved to stand as "bodies of knowledge" themselves, embodying objectual and spatial meaning in exhibitions.

Physical experimentation and simulation are two obvious potential ways through which these emergent transcalar effects can be investigated. These methods allow for a design process that can incorporate complex, multi-scalar interactions that are embodied in biological system without running into the challenges that emergent systems imply for calculus analysis. Experimentation provided empirical data and insights into organism behavior, which was essential for understanding the attributes and limitations of materials, especially those that are biologically active.

The research by design methodology has proved to be particularly effective as an integrative methodology as it fosters a continual cycle of design, testing, and refinement. The continuous testing offers several opportunities for learning from positive results that matched starting hypotheses, failures and unforeseen outcomes. This iterative process enables a gradual familiarization with the particularities of each design context. For instance, the design feasibility progression documented in the image journals, especially in *Pulp Faction*, demonstrates how the design process could evolve to accommodate insights on the performance of different parameters, in this case fungal behavior, material composition, fabrication constraints, thereby leading to more nuanced outcomes.

What kind of relevant relationships appear in scalar translations involving natural systems integrated into architecture?

The integration of natural systems into architecture inevitably gives rise to the dynamics of scalar translations. These translations are not merely shifts in magnitude and size but represent complex interdependencies that span across temporal and spatial dimensions. Several important aspects characterize these relationships, their conflicting or complementary nature, the role of serendipity, the implications for resource management, and the necessity for a realignment towards multi-scale perspectives.

Traditional engineering often operates such that the addition of one function would not impede another, except in the context of cost. In contrast, scalar translations involving natural systems often entail relationships that are not only complementary but can also be conflicting. The presence of these negative relationships isn't a drawback in itself but represents an added complexity that must be navigated. For instance, measures to optimize energy efficiency may conflict with design objectives related to aesthetic or spatial considerations. This interplay makes the process more complex, necessitating a more nuanced approach that leverages computational models capable of managing conflicting goals.

In the design, development and protocol formulation, happy accidents or serendipitous findings often emerge. These are particularly pronounced in systems where biological materials are manipulated, given their inherently complex and often unpredictable behavior. It was seen in the projects that such outcomes often serve as force multipliers in the context of design optimization (as shown in the image journals, especially regarding the biologically conditioned materiality in *Pulp Faction* and the adjusting functional forces involved in *Meristem Wall*). In such moments, the system's nonlinear behavior results in outputs that are disproportionately beneficial compared to the inputs, thereby achieving higher efficiency in resource usage.

The consideration of scalar translations involving natural systems requires a shift away from human-centric perspectives. It necessitates acknowledging the agency of other actors and elements in the ecosystem, down to the level of microorganisms. Recognizing these varying scales and perspectives can yield designs that are not only more ecologically founded but also potentially paradigm-shifting as regards the scope of what the discipline of architecture entails.

8.3. Protocols and methods

A significant contribution of this research lies in developing a comprehensive methodology for the biofabrication of fungal composites through 3d printing. Prior to this study, there had not been any formally published methods in the field that specifically addressed this novel area of biofabrication technology. This work provided an end-to-end protocol which is described in Goidea et al. (2022), beginning with the formulation of the substrate recipe, included laboratory steps and post-processing, tailored to enhance fungal growth while minimizing the risk of contamination.

A concrete contribution in this protocol was the use of xanthan gum as a stabilizer for 3d printing with fibrous materials, which does not appear to have been employed in this capacity before the publication of Goidea et al. (2020). This use has since been widely adopted in a variety of other studies focused on the extrusion of biocomposites.

More within the realm of biology was the finding that brown rot showed improved performance in fungal biocomposites compared to the more commonly used white rot of this study (Goidea et al., 2020). This finding could lead to a reassessment of the types of fungi considered optimal for biocomposite applications, and potentially open up new avenues for material development in this field.

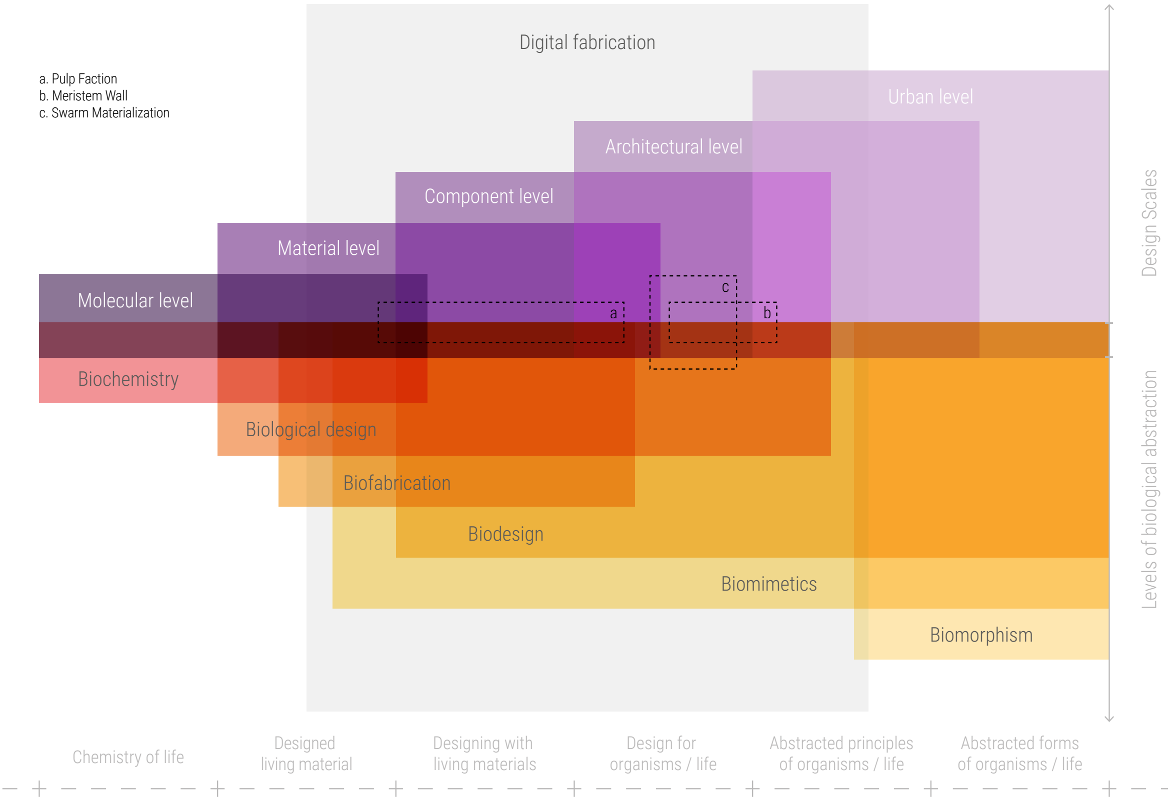


Fig. 18. Diagram showing different strategies of integrating biology in the built environment.

The methodology developed here not only fills a knowledge gap but also serves as a stepping stone for future work in the rapidly evolving field of biofabrication. While various biofabrication conditions, such as the unique genotype and behavior of specific fungal species, fluctuations in laboratory temperature, substrate sourcing, and the conditions of the fabrication environment, necessitate customization of the method, the protocols set forth provide a foundational outline. This methodology allows for future adaptations and case-specific modifications.

Another contribution of this research is the development of a computational design framework for addressing transcalarity. In this framework, nested algorithms operate at varying scales, each fulfilling specific requirements and handling potentially large datasets, the information of which constitute input at the next scale. To handle the intricate transcalar dynamics present in a biodesign endeavor, this framework involves the incorporation of multiple algorithms, each targeting different scalar objectives, rather than relying on a single algorithm with a dominant generative behavior. While this multi-algorithmic integration has been carried out manually to an extent, future iterations could allow for more automation, or interactive computational negotiation of these diverse scalar requirements in design processes.

An overall finding is that research by design is a particularly useful methodology for navigating transcalarity, as it can support contexts sitting at the intersection of several disciplines. This approach can be seen as an implementation of stigmergy, defined as indirect communication between actors of both human and more-than-human kind, through material traces left in the environment. These material traces, whether in the form of prototypes, probes, or demonstrators, effectively serve as a common ground among collaborators from different disciplines. This is particularly useful for overcoming barriers in language and methodologies that frequently impede interdisciplinary and transdisciplinary research efforts, such as between architecture and biology. Material evidence can then become the common language, enabling each discipline to recognize its own specialized knowledge made tangible, and determine pathways for progress once the cross-boundary concepts are physically realized.

Still another finding that resulted from this work is of a more theoretical kind, namely the concept of the *extended ecosystem*, (elaborated in *Meristem Wall*) which relates to the intentional design for supporting self-sustaining ecosystems within urban settings. This integrates ecological systems directly into the architectural fabric, thereby expanding on nature-based solutions through supporting biodiversity. By that, it opens up for paradigmatic shifts in architectural design thinking.

In sum, this thesis has made contributions through the framework of transcalar design in architecture, both in terms of methodological advances and empirical findings. It paves the way for future research and practical applications that encompass biodesign and biofabrication.

8.4. Notes on biodesign and sustainability

The ecological crisis we face is complex, and the changes required need to occur not only within the construction industry but extend to interconnected spheres like politics and economics. Within the architecture, engineering and construction sector, a significant emphasis within the sustainability discourse is placed on minimizing material consumption. While reducing consumption through optimization is worthwhile and necessary, this alone will not be sufficient. To enact meaningful change, it is necessary to challenge existing assumptions and modes of operation, moving away from the prevailing waste culture, while also nurturing novel approaches.

The adoption of a transcalar framework can enhance sustainability efforts by providing a comprehensive lens through which to examine the multifaceted and interconnected challenges that characterize our contemporary landscape. The contribution of this thesis is not based on market ready products or solutions where quantifiable metrics like CO_2 reduction or formal environmental impact assessments have been made, yet it places sustainability at its core; the subject pervades the rationale of many of the experiments and decisions undertaken during its course. Particular aspects that bear more direct implications for sustainability have been explored in various design experiments within this study and will be further elaborated here in these final reflections.

8.4.1. Circular construction

The concept of circularity in sustainability is an area where transcalar effects are significant, as is explicitly addressed in *Pulp Faction*. This material system based on biotransformation has the potential to utilize a wide array of fiber sources, including those from waste, upcycling it into valuable materials at a molecular level. There is a potential for a vast library of fungal (or other microbes) strains that can grow on a diverse substrate composition. This would result in a material system able to adapt to resource availability, and result in biocomposites with different properties suitable for varying architectural performances (Andréen & Goidea, 2022). Such a fabrication approach does not further increase the current dependence on monocultures. This could otherwise be a significant critique of a biobased shift, if undertaken in a standardized and homogenized large scale production manner, due to detrimental effects on ecological sustainability. However, lignocellulosic fibers can be obtained from abundant, renewable sources, from agriculture or other industries as byproducts (Dahy, 2019).

Relying on a biotransformation process, rather than on synthetic derivatives for binding the substrate fibers yields wood-based composites compostable (Van Wylick et al., 2022). These materials also possess the capacity for continual recycling by incorporating new cellulose fibers into their composition. Furthermore, the inclusion of biotransformation at the molecular scale can offer benefits in terms of the recyclability of fibrous materials that deteriorate through fiber shortening in conventional mechanical recycling systems.

Through the design experiment, it became apparent that the scalability of these materials to architectural applications was facilitated by digital fabrication and design technologies. These processes make it possible to combine the scale of implementation necessary for meaningful impact with the articulation, variation, and specificity that is necessary to accommodate the combined requirements of these diverse microorganisms and the human needs. This adaptability in both design and fabrication helps to avoid the pitfalls of centralized mass production and is aligned with the inherent logic of the material system, thereby enhancing the potential to preserve a wider range of their benefits.

8.4.2. Humans and the ecosystem

Another aspect that was addressed in this thesis was the subject of biodiversity and the relationship between the built and natural environments. *Meristem Wall* was used as an arena for experimenting how these seemingly separate realms can be integrated. Rather than creating a binary separation where space is allocated exclusively for either human environments or non-human ecosystems, the project proposes an interconnected approach that acts in the service of both. We have come to expect human habitats to be free of biological life in their natural state, only tolerating controlled and ordered expressions of nature. I have argued that this duality is deceptive, and the aim for sterile environments leads to the prevalence of pests and ecosystems that are out of balance.

Instead, if we incorporate the requirements for a functional, healthy ecosystem in our built environment, we can improve the existence not only for the nonhuman ecosystem but for ourselves. An interconnected transcalar perspective that I have proposed throughout this thesis can aid this.

8.4.3. Building physiology

Using biological principles of physiology to modulate and affect building climates that holds potential for reduced energy requirements of buildings. These principles depend on mechanisms such as folding, interconnectedness and high surface areas, and require the integration of smaller scales in the building structures and envelope. Here the need to consider and have tools and processes that can manage transcalar interdependence is of great importance.

Meristem Wall demonstrated how such systems can be designed to integrate low-energy input systems for regulating indoor environments. By functioning as an active membrane, the wall leverages the energy of its surrounding environment to modulate the internal conditions. This inclusion reduces the building's reliance on energy-intensive systems for ventilation and climate control. The designed performance of *Meristem Wall* to act as a dynamically responsive boundary, promotes a more multidimensional interaction between architecture and its surroundings (Andréen & Goidea, 2022). Without the ability to construct highly articulated and specific component shapes, and to relate them to the larger scales of the building itself and its surroundings, such as is suggested by transcalarity, these mechanisms could not have been implemented in a building envelope.

The example of *Meristem Wall* is just one opportunity for such semi-passive climate regulation mechanisms. I believe that the ability to build with transcalar considerations has the potential to extend the reach and effectiveness of similar mechanisms.

8.4.4. Low impact materials

In two of the design experiments the raw materials involved are not heavily engineered or precious, and in all projects the material performativity as part of architectural systems was enhanced through transcalar principles, whether it was the biotransformation in *Pulp*

Faction, the graded functional geometries of *Meristem Wall*, or the responsiveness to nonlinear material behavior in both design and fabrication in the *Swarm Materialization* process. This potentially reduces the need for resource-intense materials and processing, as well as transport and centralized infrastructure. Such materials, prevalent in vernacular architecture, have to a great extent left the contemporary palette, and the emergence of a new design and fabrication paradigm can lead to their resurgence.

These issues are perhaps most directly evident in *Swarm Materialization*. First, the project advances a material framework that is characterized by reversibility, locality, and malleability. While materials such as earth have several environmental benefits, this strategy acknowledges the inherent complexities and sometimes challenging properties of local, anisotropic materials. The project employs computational strategies to manage these complexities, thus integrating these sustainable materials into contemporary architectural practice. Beyond the enhancement to use local materiality, the incorporation of feedback systems in construction such as the one outlined in this design experiment allow for the encoding of not shapes, but processes and relationships (Andréen & Goidea, 2022). A more adaptive and responsive architecture can then be generated, as it is more aligned with the emergence of phenotypes in organisms.

8.4.5. An architecture of continuous change

The last project proposed the setup of a feedback system that not only allows for adaptations, but also holds the potential for automated maintenance and alterations. This strategy aligns with the broader goal of employing less permanent, weaker materials through adopting resilience – seen here as the capacity to adapt to change while maintaining functionality – rather than permanence.

Through methods such as these there could be a resurgence of continual maintenance as a valid architectural strategy, as employed in traditional vernacular structures such as mud and rammed earth buildings. A conventional approach to construction may require a shift in the current relationship between users and the built environment, to require more involvement, but it is plausible that technological advancements can facilitate this shift. Advances in distributed robotics and digital fabrication technologies offer the possibility to shoulder the burden of this upkeep, therefore making it a viable approach in the contemporary context. The proposed methods for machine vision, adaptation and feedback may prove to be useful in the development of such distributed and automated construction.

The temporal aspects of the construction process are sometimes as important as the spatial ones in the consideration of transcalarity: having a building process that is able to integrate with past building practice without tearing down and starting over with a new system. The methods investigated here provide tools for such an integration: fungal composites can be integrated in refurbishing or retrofitting, the ability to adapt new construction to old geometries through scanning, volumetric modeling and 3d printing, or the continuous, feedback-driven design and construction process proposed in *Swarm Materialization*.

The potential for construction to run in parallel with occupation reduces the need for large construction projects to be rapidly completed, which is one of the drivers for standardization and centralization in the building industry, opening up for the integration of more sustainable alternatives (Andréen & Goidea, 2022). The project thus proposes a new model where the timelines for maintenance, fabrication, repair, and recycling are closely intertwined.

While the aim of this approach is not to entirely replace all current materials in the architectural infrastructure of cities, it can provide a framework for a large portion of them which can and should be replaced, as in the following suggestion: “Bulk material is sustainably sourced and processed, and it is complemented by high-energy, high-performance materials that are employed more selectively and with greater criticality” (Andréen & Goidea, 2022, pp. 9).

8.4.6. On homeodynamic built environments

I will conclude with a speculative narrative for integrating various models on sustainability explored in this thesis. The soil excavated during the foundational stages of construction can be employed as material for segments or components of the building. These can be maintained by systems of swarm robotics employing sensor systems that adapt to the building’s needs during seasonal changes and other variables. Additionally, fibrous materials could be grown in extended ecosystems that are integrated into the building's envelope. These fibers might then be utilized in the biofabrication of composites for other sections of the building, such as interior systems. When these components eventually degrade or become obsolete, they can be repurposed as compost back into the urban ecosystems where they originated. Such a framework intertwines concepts of biodiversity, circularity, and adaptation — ranging from microbial ecosystem processes and biofabrication to diverse timescales, including seasonal changes — transforming buildings into homeodynamic environments (Andréen & Goidea, 2022).

These are theoretical speculations of course, and more studies and developments need to be elaborated to verify the viability and applicability of such models. However, we are in need of alternatives to construction paradigms. The work here suggests some strategies for construction and maintenance grounded in local sourcing, ecosystem development, vernacular traditions, and digital technologies. All these elements converge to address sustainability concerns through a transcalar lens, emphasizing the need for ongoing research and development to further test and implement these approaches.

8.5. Concluding remarks

This dissertation has been a journey through the intricate relationships that define biodesign and biofabrication, with a focus on transcalar design as a critical perspective. At its core, transcalar design integrates various elements across multiple scales — biological, material, and design considerations — thereby offering an integrative framework for biodesign and additive manufacturing in architecture.

The three design experiments that form the body of this dissertation — *Pulp Faction*, *Meristem Wall*, and *Swarm Materialization* — each illuminate different facets of transcalar design. They collectively illustrate how this design approach can influence material selection, enable an articulated algorithmic planning, and facilitate cross-disciplinary collaboration. These projects not only demonstrate the utility of transcalar design but also embody its potential in diversifying the field of architecture and biofabrication.

As we consider future trajectories, it's worth considering what a "new building culture" might mean, equipped with advanced planning methods, novel building materials, and innovative building processes to meet the 21st-century challenges (Knippers et al., 2021). This dissertation argues that transcalar design could be a new approach in design strategies, aligning material science, biology, and architecture in unprecedented ways.

Furthermore, as remote as microbiology laboratories may seem from the sphere of mainstream architectural production, it is relevant to remember pivotal moments in history that brought biotechnology to the forefront. The discovery of penicillin, for example, triggered a golden age in biotechnology, transforming sterile fermentation processes into industrial-scale applications in a remarkably short period. It is possible that we are now at the brink of a similar leap, but now in the realm of architectural production: an architectural biotechnology, for the integration of biological processes into the built environment, from microorganism to ecosystem scale.

As with any research endeavor, this dissertation poses as many questions as it answers, opening up for further investigations. If biofabrication is to be scaled up to widespread adoption in the building industry, how can it be made performative and efficient enough to be economically sustainable? What fungal species and strains are best used to different local contexts, and how is this variation managed in a design and construction process? How can raw materials be sourced at large volumes in sustainable ways?

The three different design experiments developed widely different methods and approaches, but they all incorporate aspects that are fundamental for a transcalar paradigm – how can these come together in processes and projects that combine their strengths? Is it possible to achieve a unified framework for transcalar design, or should every solution develop its own process based on an ever-expanding toolkit?

If the design and construction industry is facing a disruptive paradigm shift, how can we ensure that the benefits of this new paradigm are shared more equally by all parts of society and all across the globe? And what are the ethical and societal implications of adopting an ecosystem-centric view in urban planning and architecture? These questions, among others, offer exciting avenues for future research.

Thank you for accompanying me on this exploratory journey through scales. It is my hope that this work will serve as a catalyst for further inquiry into the intricate scalar world of biodesign in architecture.

References

3D Printed bridge. IAAC. (2021, December 17). https://iaac.net/project/3d-printed-bridge/

Acanthus. (n.d.). *Britannica Online*. https://www.britannica.com/art/acanthus-ornamental-motif

Alberts, B., Heald, R., Johnson, A., Morgan, D., Raff, M., Roberts, K., & Walter, P. (2022). *Molecular biology of the cell* (seventh edition). W. W. Norton & Company.

Andréen, D. (2016). *Discriminatory transient mass transfer through reticulated network geometries: a mechanism for integrating functionalities in the building envelope*. EngD thesis, UCL (University College London), London.

Andréen, D. & Goidea A. (2022). Principles of biological design as a model for biodesign and biofabrication in architecture. *Architecture. Structures. Construction*, 2, pp. 481–491. https://doi.org/10.1007/s44150-022-00049-6

Andreen, D., Goidea, A., Johansson, A., & Hildorsson, E. (2019). Swarm materialization through discrete, nonsequential additive fabrication. *2019 IEEE 4th International Workshops on Foundations and Applications of Self* Systems (FAS*W)*. https://doi.org/10.1109/fas-w.2019.00059

Andréen, D., & Soar, R. (2023). Termite-inspired metamaterials for flow-active building envelopes. *Frontiers in Materials*, *10*. https://doi.org/10.3389/fmats.2023.1126974

Anker, P. (2006). Science in culture: Bauhaus at the zoo. *Nature*, *439*(7079), 916–916. https://doi.org/10.1038/439916a

Arshad, M. A., & Schnitzer, M. (1987). The chemistry of a termite fungus comb. *Plant and Soil*, 98(2), 247–256. http://www.jstor.org/stable/42936164

Augugliaro, F., & D'Andrea, R. (2015). *Aerial construction*. Institute for Dynamic Systems and Control | ETH Zurich. https://idsc.ethz.ch/research-dandrea/research-projects/aerial-construction.html

Bechtel, W., & Richardson, R. C. (1998). Vitalism. *Routledge Encyclopedia of Philosophy*. https://doi.org/10.4324/9780415249126-q109-1

Beesley, P., Sachiko H., & Ruxton, J. (2006). 'Toward Responsive Architectures.' *Responsive Architectures : Subtle Technologies*. Eds. Philip Beesley, Sachiko Hirosue, Jim Ruxton, M. Trankle and C. Turner. Toronto: Riverside Architectural Press. Print. 3-11.

Beesley, P. (2020). Diagrams of Entropic Forces: Design For New Dissipative Fabrication. *Fabricate 2020*, 256–263.

Bennett, J. W. (1998). Mycotechnology: The role of fungi in biotechnology. *Journal of Biotechnology*, *66*(2-3), 101–107. https://doi.org/10.1016/s0168-1656(98)00133-3

Bentley, P. (2007). Climbing Through Complexity Ceilings. In A. Burke & T. Tierney (Eds.), Network practices: new strategies in architecture and design, pp. 178–197. Princeton Architectural Press.

Berman, M. G., Kross, E., Krpan, K. M., Askren, M. K., Burson, A., Deldin, P. J., Kaplan, S., Sherdell, L., Gotlib, I. H., & Jonides, J. (2012). Interacting with nature improves cognition and affect for individuals with depression. *Journal of affective disorders*, *140*(3), 300–305. https://doi.org/10.1016/j.jad.2012.03.012

Bilotti, J., Norman, B., Rosenwasser, D., Leo Liu, J., & Sabin, J. E. (2018). Robosense 2.0. Robotic Sensing and architectural ceramic fabrication. *Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. https://doi.org/10.52842/conf.acadia.2018.276

Bouaziz, O., Bréchet, Y., & Embury, J. D. (2008). Heterogeneous and architectured materials: A possible strategy for design of Structural Materials. *Advanced Engineering Materials*, *10*(1-2), 24–36.

Bud, R. (1991). Biotechnology in the Twentieth Century. *Social Studies of Science*, *21*(3), 415–457. https://doi.org/10.1177/030631291021003002

Cambridge Dictionary. (n.d.). Scale. In dictionary.cambridge.org dictionary. https://dictionary.cambridge.org/dictionary/english/scale

Caron, J. A. (1988). ‘biology’ in the life sciences: A historiographical contribution. *History of Science*, *26*(3), 223–268. https://doi.org/10.1177/007327538802600301

Carpo, M. (2023). A short but believable history of the digital turn in architecture. *E-Flux Architecture*, *Chronograms of Architecture*.

Catts, O., & Zurr, I. (2013). The vitality of matter and the instrumentalisation of life. *Architectural Design*, *83*(1), 70–75. https://doi.org/10.1002/ad.1527

Churchman, C.W. (1970). ‘Operations Research as a Profession’. *Management Science* 17(2): pp. B37-53.

Clay Rotunda, SE MusicLab, Bern, 2020-2021. Gramazio Kohler Research. (n.d.). https://gramaziokohler.arch.ethz.ch/web/e/projekte/430.html

Complex. (n.d.). *Online Etymology Dictionary*. https://www.etymonline.com/word/complex

Cox, D. T. C., Shanahan, D. F., Hudson, H. L., Fuller, R. A., & Gaston, K. J. (2018). The impact of urbanisation on nature dose and the implications for human health. *Landscape and Urban Planning*, *179*, 72–80. https://doi.org/10.1016/j.landurbplan.2018.07.013

Crutzen, P. J. & Stoermer, E. F. (2000). *IGBP Newsletter* 41, Royal Swedish Academy of Sciences, Stockholm.

Dahy, H. (2019). Natural Fibre-Reinforced Polymer Composites (NFRP) Fabricated from Lignocellulosic Fibres for Future Sustainable Architectural Applications, Case Studies: Segmented-Shell Construction, Acoustic Panels, and Furniture. *Sensors*, *19*(3), 738. https://doi.org/10.3390/s19030738

De Landa, M. (1995). Uniformity and variability. An Essay in the Philosophy of Matter. https://www.cddc.vt.edu/host/delanda/pages/uniformity1.htm

Dierichs, K., & Menges, A. (2012). Aggregate structures: Material and machine computation of designed granular substances. *Architectural Design*, *82*(2), 74–81. https://doi.org/10.1002/ad.1382

Dillenburger, B., & Hansmeyer, H. (2014). *Printing Architecture: Castles made of Sand.* Fabricate: Negotiating Design and Making, 92–97.

Dini, E. (2009). D-SHAPE-The 21st century revolution in building technology has a name. *London, England*, 1-16.

Dobson, J., Birch, J., Brindley, P., Henneberry, J., McEwan, K., Mears, M., Richardson, M., & Jorgensen, A. (2021). The magic of the mundane: The vulnerable web of connections between urban nature and wellbeing. *Cities*, *108*, 102989. https://doi.org/10.1016/j.cities.2020.102989

Dörfler, K., Ernst, S., Piskorec, L., Willmann, J., Helm, V., Gramazio, F., & Kohler, M. D. (2014). REMOTE MATERIAL DEPOSITION: Exploration of Reciprocal Digital and Material Computational Capacities. In *What's the Matter – Materiality and Materialism at the Age of Computation, International Conference*. Barcelona; COAC, ETSAB, ETSAV.

Dörfler, K., Hack, N., Henke, K., & Kloft, H. (2023). In *AMC COLLABORATIVE DEMONSTRATORS. Validation of Integrated Research Methodologies through Collaborative AMC Prototyping*. Technische Universität Braunschweig. pp. 84–97.

Dunn, R. (2018). *Never home alone: From microbes to millipedes, camel crickets, and honeybees, the natural... history of where we live*. Basic Books.

Ednie-Brown, P. (2013). Biomason and the speculative engagements of Biotechnical architecture. *Architectural Design*, *83*(1), 84–91. https://doi.org/10.1002/ad.1529

Elsacker, E. V. (2021). *Mycelium matters - an interdisciplinary exploration of the fabrication and properties of mycelium-based materials*. VUBPress.

Elsacker, E. V., Søndergaard, A., Van Wylick, A., Peeters, E., & De Laet, L. (2021). Growing living and multifunctional mycelium composites for large-scale formwork applications using robotic abrasive wire-cutting. *Construction and Building Materials*, *283*, 122732. https://doi.org/10.1016/j.conbuildmat.2021.122732

European Comission. (2018, September 18). *EU construction and Demolition Waste Protocol*. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Retrieved February 1, 2022, from https://ec.europa.eu/growth/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en

Eurostat (2018). *Waste statistics*. Retrieved February 1, 2022, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation

Findeli, A., Brouillet, D., Martin, S., Moineau, C., & Tarrago, R. (2008). Research Through Design and Transdisciplinarity: A Tentative Contribution to the Methodology of Design Research, in *FOCUSED— Current Design Research Projects and Methods*, Swiss Design Network Symposium, Université de Montréal.

Frayling, C. (1993). *Research in Art and Design*, London: Royal College of Art Research Papers.

Gamble, C. N., Hanan, J. S. & Nail, T. (2019) WHAT IS NEW MATERIALISM?, Angelaki, 24:6, 111-134, DOI: 10.1080/0969725X.2019.1684704

Ghasemi-Mobarakeh, L., Kolahreez, D., Ramakrishna, S., & Williams, D. (2019). Key terminology in biomaterials and biocompatibility. *Current Opinion in Biomedical Engineering*, *10*, 45–50. https://doi.org/10.1016/j.cobme.2019.02.004

Gibson, J. J. (1979). *The ecological approach to visual perception*. Psychology Press, 2015.

Gil Pérez, M., Zechmeister, C., Kannenberg, F., Mindermann, P., Balangé, L., Guo, Y., Hügle, S., Gienger, A., Forster, D., Bischoff, M., Tarín, C., Middendorf, P., Schwieger, V., Gresser, G. T., Menges, A., & Knippers, J. (2022). Computational co-design framework for coreless wound fibre–polymer composite structures. *Journal of Computational Design and Engineering*, *9*(2), 310–329. https://doi.org/10.1093/jcde/qwab081

Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme (2019): 2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector.

Goidea, A., Floudas, D., & Andréen, D. (2020). Pulp Faction: 3d printed material assemblies through microbial biotransformation. *Fabricate 2020: Making Resilient Architecture*, London, 2020, 42-49.

Goidea, A., Floudas, D. & Andréen, D. (2022). Transcalar Design: An Approach to Biodesign in the Built Environment. *Infrastructures*, 7(4):50.

Goidea, A., Popescu, M. & Andréen, D. (2021). Meristem Wall an exploration of 3d printed architecture. *ACADIA 2021: Realignments: Toward Critical Computation*. Edited by Bogosian, B., Dörfler, K., Farahi, B., Garcia del Castillo y López, J., Grant, J., Noel ,V., Parascho, S., & Scott ,J. pp. 438-443.

Gonchar, J. (2019). Snake charmer: a trio of buildings for a watchmaking company reveals new possibilities for wood. *Architectural Record*, *207*(12), 74–82.

Gordon, J. E. (1988). *The science of structures and materials*. Scientific American Library.

Grassé, P. (1959). La reconstruction du nid et les coordinations interindividuelles chez Bellicositermes natalensis et Cubitermes sp. la théorie de la stigmergie: Essai d’interprétation du comportement des termites constructeurs. *Insectes Sociaux*, *6*(1), 41–80. https://doi.org/10.1007/BF02223791

Greenspoon, L., Krieger, E., Sender, R., Rosenberg, Y., Bar-On, Y. M., Moran, U., Antman, T., Meiri, S., Roll, U., Noor, E., & Milo, R. (2023). The global biomass of Wild Mammals. *Proceedings of the National Academy of Sciences*, *120*(10). https://doi.org/10.1073/pnas.2204892120

Hahn, J. (2022). *Blast Studio 3D prints column from mycelium to make "architecture that could feed people."* Dezeen. https://www.dezeen.com/2022/01/18/blast-studio-tree-column-mycelium-design/

Hansmeyer, M., & Dillenburger, B. (2013). Digital grotesque I. Michael Hansmeyer - Computational Architecture. https://www.michael-hansmeyer.com/digital-grotesque-I

Hawksworth, D. L., & Lücking, R. (2017). Fungal diversity revisited: 2.2 to 3.8 million species. *The Fungal Kingdom*. Edited by J. Heitman & T. Y. James. American Society for Microbiology. 79–95. https://doi.org/10.1128/9781555819583.ch4

Heynen, H. (2012). Genius, Gender and Architecture: The Star System as Exemplified in the Pritzker Prize. *Architectural Theory Review*, *17*(2/3), 331–345. https://doi-org.ludwig.lub.lu.se/10.1080/13264826.2012.727443

Hendrix, J. S., (2011). Leon Battista Alberti and the Concept of Lineament. *School of Architecture, Art, and Historic Preservation Faculty Publications*. Paper 30.

Heisel, F., Lee, J., Schlesier, K., Rippmann, M., Saeidi, N., Javadian, A., Nugroho, A. R., Mele, T. V., Block, P., & Hebel, D. E. (2017). Design, cultivation and application of load-bearing mycelium components: The MycoTree at the 2017 Seoul biennale of architecture and urbanism. *International Journal of Sustainable Energy Development*, *6*(1), 296–303. https://doi.org/10.20533/ijsed.2046.3707.2017.0039

Hensel, M. (2012). *Performance-oriented Architecture – An integrated discourse and theoretical framework for architectural design and sustainability towards non-discrete and non-anthropocentric architectures*. University of Reading.

Higgs, E. (2016). Novel and designed ecosystems. *Restoration Ecology*, *25*(1), 8–13. https://doi.org/10.1111/rec.12410

Hinkelmann, K., & Kempthorne, O. (1994). *Design and Analysis of Experiments, Introduction to Experimental Design*. John Wiley & Sons.

Hirata, (2016). *A Japanese Constellation: Toyo Ito, SANAA, and Beyond*. (The Museum of Modern Art, New York, 2016).

Horton, Z. K. (2021). *The cosmic zoom: Scale, knowledge, and Mediation*. The University of Chicago Press.

Houck, M.M. (2009). 8 - The use of spectroscopy for textile fiber identification. In *Identification of Textile Fibers*. Woodhead Publishing Series in Textiles. Editor: Max M. Houck. Woodhead Publishing, pp. 158-164. https://doi.org/10.1533/9781845695651.2.158.

Jaque, A. (2022, March). *Transscalar Architecture*. *The Berlage Keynotes*. TU Delft.

Jarzombek, M., & Prakāsh, V. (2020). Many Houses, Many Worlds. *O(U)R Office of (Un) certainty Research* [officeofuncertaintyresearch.org].

Johnson, S. (2002). *Emergence: The connected lives of ants, brains, cities, and software*. Simon & Schuster.

Jones, M. S., Fu, Z., Reganold, J. P., Karp, D. S., Besser, T. E., Tylianakis, J. M., & Snyder, W. E. (2019). Organic farming promotes biotic resistance to foodborne human pathogens. *Journal of Applied Ecology*, *56*(5), 1117–1127. https://doi.org/10.1111/1365-2664.13365

Kendrick, B. (2017). Kingdoms, Classification, Nomenclature, and Biodiversity. In *The Fifth Kingdom* (Fourth Edition). Hackett Publishing Company.

Knippers, J., Kropp, C., Menges, A., Sawodny, O., & Weiskopf, D. (2021). Integrative Computational Design and Construction: Rethinking Architecture digitally. *Civil Engineering Design*, *3*(4), 123–135. https://doi.org/10.1002/cend.202100027

Lang, J. M., Coil, D. A., Neches, R. Y., Brown, W. E., Cavalier, D., Severance, M., Hampton-Marcell, J. T., Gilbert, J. A., & Eisen, J. A. (2017). A microbial survey of the International Space Station (ISS). *PeerJ*, *5*. https://doi.org/10.7717/peerj.4029

Larson, C. (2016). Evidence of Shared Aspects of Complexity Science and Quantum Phenomena. *Cosmos and History: The Journal of Natural and Social Philosophy*, *12*(2), 160–171.

Learn Genetics. (n.d.). The Glycogenolysis Signaling Cascade. University of Utah. Retrieved 2023.

Lee, S., Congdon, A., Parker, G., & Borst, C. (2021). *Understanding "Bio" Material Innovations Report*. Biofabricate. https://app.box.com/s/amjq9anszv8hvwdexoxg6wubes4aaxqa

Lewis, S. L., & Maslin, M. A. (2015). Defining the anthropocene. *Nature*, *519*(7542), 171–180. https://doi.org/10.1038/nature14258

Lewis T., & Stone W.L. (2022). Biochemistry, Proteins Enzymes. StatPearls. Treasure Island (FL): *StatPearls Publishing*; 2023 Jan. https://www.ncbi.nlm.nih.gov/books/NBK554481/

Lim, A. C., & Ramsgaard Thomsen, M.(2021). Multi-Material Fabrication for Biodegradable Structures. Enabling the printing of porous mycelium composite structures. *Proceedings of the 39th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)*. https://doi.org/10.52842/conf.ecaade.2021.1.085

Linder, M. B., Szilvay, G. R., Nakari-Setälä, T., & Penttilä, M. E. (2005). Hydrophobins: The protein-amphiphiles of filamentous fungi. *FEMS Microbiology Reviews*, 29(5), 877–896. https://doi.org/10.1016/j.femsre.2005.01.004

Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C., & Dillenburger, B. (2018). Particle-bed 3D printing in concrete construction – possibilities and challenges. *Cement and Concrete Research*, *112*, 50–65. https://doi.org/10.1016/j.cemconres.2018.05.018

Mateos, J. L. (2009). Complex Systems and Non-linear Dynamics . In J. L. Mora-Lopez (Ed.), *FUNDAMENTALS OF PHYSICS* (Vol. I, pp. 356–370). essay, EOLSS Publication.

Melton, L. (2022). How to grow cement. *Nature Biotechnology*, *40*(3), 286–286. https://doi.org/10.1038/s41587-022-01264-8

Menges, A. (2010). Material systems, computational morphogenesis and performative capacity. In Hensel, M., Menges, A. & Weinstock, M. (Eds.), *Emergent Technologies and Design: Towards a biological paradigm for architecture* (1st ed, pp. 194–208). Routledge. https://doi.org/10.4324/9781315881294

Menges, A. (2012), Material Computation: Higher Integration in Morphogenetic Design. *Architectural Design*, 82: 14-21. https://doi.org/10.1002/ad.1374

Midgley, G. (2000). *Systemic Intervention – Philosophy, Methodology and Practice*.

Miller, J. R., & Hobbs, R. J. (2002). Conservation where people live and work. *Conservation Biology*, *16*(2), 330–337. https://doi.org/10.1046/j.1523-1739.2002.00420.x

Ming, C., Mirjan, A., Medina Ibáñez, J., Gramazio, F., & Kohler, M. (2022). Impact printing. *3D Printing and Additive Manufacturing*, *9*(3), 203–211. https://doi.org/10.1089/3dp.2021.0068

Miranda, P., & Coates, P. (2000). *Swarm modelling. The use of Swarm Intelligence to generate architectural form*. http://papers.cumincad.org/cgi-bin/works/Show?_id=39c6&sort=DEFAULT&search=swarm&hits=32

Mirjan, A., Gramazio, F., Kohler, M., Augugliaro, F., & D'Andrea, R. (2013b). Architectural fabrication of tensile structures with flying machines. *Green Design, Materials and Manufacturing Processes*, 513–518. https://doi.org/10.1201/b15002-99

Mok, K. (Updated 2018). *Mycotecture: Building with Mushrooms? This Inventor Says Yes*. Treehugger. https://www.treehugger.com/mycotecture-mushroom-bricks-philip-ross-4857225.

Money, N. P. (2016). Fungi and biotechnology. *The Fungi*, 401–424. https://doi.org/10.1016/b978-0-12-382034-1.00012-8

Moroni, L., Boland, T., Burdick, J. A., De Maria, C., Derby, B., Forgacs, G., Groll, J., Li, Q., Malda, J., Mironov, V. A., Mota, C., Nakamura, M., Shu, W., Takeuchi, S., Woodfield, T. B. F., Xu, T., Yoo, J. J., & Vozzi, G. (2018). Biofabrication: A guide to technology and terminology. *Trends in Biotechnology*, *36*(4), 384–402. https://doi.org/10.1016/j.tibtech.2017.10.015

Morton, T. (2018). *Dark ecology: For a logic of future coexistence*. Columbia University Press.

Myers, W., & Antonelli, P. (2012). Beyond biomimicry. *In Bio design: Nature, science, creativity* (pp. 10–17). Introduction, Thames & Hudson Ltd., London.

Nagy, D., Locke, J., & Benjamin, D. (2015). Computational Brick Stacking for Constructing Free-Form Structures. In: Thomsen, M., Tamke, M., Gengnagel, C., Faircloth, B., Scheurer, F. (eds) *Modelling Behaviour*. Springer, Cham. https://doi.org/10.1007/978-3-319-24208-8_17

Nature-based solutions. Nature-Based Solutions | Environment - Research and Innovation - European Commission. (2017, January 9). Retrieved January 29, 2022, from https://web.archive.org/web/20190923161801/http://ec.europa.eu/research/environment/index.cfm?pg=nbs

Nicholas, P., Stasiuk, D., Nørgaard, E. C., Hutchinson, C., & Thomsen, M. R. (2015). A multiscale adaptive mesh refinement approach to architectured steel specification in the design of a frameless stressed skin structure. *Modelling Behaviour*, 17–34. https://doi.org/10.1007/978-3-319-24208-8_2

Nicholas, P., Zwierzycki, M., Stasiuk, D., Norgaard, E., & Thomsen, M. R. (2016). Concepts and methodologies for Multiscale Modeling: A Mesh-based approach for bi-directional information flows. *ACADIA Proceedings*. https://doi.org/10.52842/conf.acadia.2016.308

Noble, D. (2008). *The music of Life: Biology Beyond Genes*. Oxford University Press.

O'Connor, J. (2004). Survey on actual service lives for North American buildings. [Paper presentation]. Woodframe Housing Durability and Disaster Issues conference, Las Vegas, October 2004.

Officina Corpuscoli & Co-de-iT. (2019). *Bio Ex-Machina*. Officina Corpuscoli. https://www.corpuscoli.com/projects/bio-ex-machina/

Otto, F. (1971). *IL3 Biology and Building Part 1*. Stuttgart: University of Stuttgart.

Otto, F. (1988). *Apparatus for computing minimal path systems*. Institute for Lightweight Structures (ILEK), Stuttgart.

Oxman, N. (2010). *Material-based design computation* (thesis). Massachusetts Institute of Technology.

Oxman, N., Ortiz, C., Gramazio, F., & Kohler, M. (2015). Material ecology. *Computer-Aided Design*, *60*, 1–2. https://doi-org.ludwig.lub.lu.se/10.1016/j.cad.2014.05.009

Petersen, K. H., Napp, N., Stuart-Smith, R., Rus, D., & Kovac, M. (2019). A review of collective robotic construction. *Science Robotics*, *4*(28). https://doi.org/10.1126/scirobotics.aau8479

Pigliucci M. (2010). Genotype-phenotype mapping and the end of the 'genes as blueprint' metaphor. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *365* (1540), 557–566.

Piker, D. (2013). Kangaroo: Form finding with computational physics. *Architectural Design*, *83*(2), 136–137. https://doi.org/10.1002/ad.1569

Poinet, P., Nicholas, P., Tamke, M., & Ramsgaard Thomsen, M. (2016). Multi-Scalar Modelling for Free-form Timber Structures. In K. Kawaguchi, M. Ohsak, & T. Takeuchi (Eds.), *Proceedings of the IASS Annual Symposium 2016: Spatial Structures in the 21st Century.*

Prosser, C. L. (1991). In *Comparative animal physiology. environmental and Metabolic Animal Physiology* (pp. 1–2). Wiley-Liss.

Ramachandra Rao, S. (2006). Resource recovery from process wastes. *Resource Recovery and Recycling from Metallurgical Wastes*, 375–457. https://doi.org/10.1016/s0713-2743(06)80095-4

Ramsgaard Thomsen, M., & Tamke, M. (2009). Narratives of making: thinking practice led research in architecture, *Communicating (by) Design* 2009, 1-8.

Ramsgaard Thomsen, M., & Tamke, M. (2016). Prototyping Practice: Merging Digital and Physical Enquiries. In: Gengnagel, C., Nagy, E., Stark, R. (eds) *Rethink! Prototyping*. Springer, Cham. https://doi.org/10.1007/978-3-319-24439-6_5

Ramsgaard Thomsen, M. R., & Tamke, M. (2022). Towards a transformational eco-metabolistic bio-based design framework in architecture. *Bioinspiration & Biomimetics*, 17(4), 045005. https://doi.org/10.1088/1748-3190/ac62e2

Regenmortel, M. H. (2004). Reductionism and complexity in Molecular Biology. *European Molecular Biology Organization Reports*, *5*(11), 1016–1020. https://doi.org/10.1038/sj.embor.7400284

Ritchie H., Roser M. (2018) Urbanization. *Published online at OurWorldInData.org.* Retrieved from: ‘https://ourworldindata.org/urbanization’ [Online Resource]

Redwood, B., Schöffer Filemon, Garrett, B., & Fadell, T. (2020). T*he 3D Printing Handbook Technologies, design and applications.* 3D Hubs.

Roggema, R. (2017). Research by Design: Proposition for a Methodological Approach, *Urban Sci. 1(1), 2*. http://doi.org/10.3390/urbansci1010002

Rosenthal M., Henneberger C., Gutkes A., & Bues CT. (2017). Liquid Deposition Modeling: A Promising Approach for 3D Printing of Wood. *European Journal of Wood and Wood Products* 76, no. 2, pp 797-99 (797).

Rossi, G., Chiujdea, R.-S., Hochegger, L., Lharchi, A., Harding, J., Nicholas, P., Tamke, M., & Thomsen, M. R. (2022). Statistically modelling the curing of cellulose-based 3D printed components: Methods for material dataset composition, augmentation and encoding. *Towards Radical Regeneration*, 487–500. https://doi.org/10.1007/978-3-031-13249-0_39

Sabin, J. E., Jones, P. L., Carpo, M., & Lucia, A. (2018). *LabStudio design research between architecture and biology*. Routledge, Taylor & Francis Group.

Sangma, J. S. A., & Prasad, S. B. (2021). Population and Nesting Behaviour of Weaver Ants, Oecophylla smaragdina from Meghalaya, India. *Sociobiology*, *68*(4), e7204. https://doi.org/10.13102/sociobiology.v68i4.7204

Scholte, J. A. (2019). Civil society and global governance: Exploring transscalar connections. *Interest Groups & Advocacy*, 486 8(3), 490–498.

Segré, D., Ben-Eli, D., Deamer, D. W., & Lancet, D. (2001). The lipid world. *Origins of Life and Evolution of the Biosphere*, *31*(1/2), 119–145. https://doi.org/10.1023/a:1006746807104

Sezer, A. A., Thunberg, M., & Wernicke, B. (2021). Digitalization index: Developing a model for assessing the degree of digitalization of construction projects. *Journal of Construction Engineering and Management*, 147(10). https://doi.org/10.1061/(asce)co.1943-7862.0002145

Sharma S. (2020). Designing the Organism-Environment Relationship (Unpublished doctoral dissertation), Massachusetts Institute of Technology, Cambridge, Massachusetts.

Smith, C. S. (1982). Matter Versus Materials. In *A search for structure: Selected essays on science, art, and history*. MIT Press.

Soanes, K., & Lentini, P. E. (2019). When cities are the last chance for saving species. *Frontiers in Ecology and the Environment*, *17*(4), 225–231. https://doi.org/10.1002/fee.2032

Southern, J. (2015). *Sci-Arc Offramp*. Models Lie. https://offramp.sciarc.edu/articles/models-lie

Southon, G. E., Jorgensen, A., Dunnett, N., Hoyle, H., & Evans, K. L. (2018). Perceived species-richness in urban green spaces: Cues, accuracy and well-being impacts. *Landscape and Urban Planning*, *172*, 1–10. https://doi.org/10.1016/j.landurbplan.2017.12.002

Sutherland, I. E. (1964). Sketchpad a Man-Machine Graphical Communication System. *SIMULATION*, 2(5), R-3. https://doi.org/10.1177/003754976400200514

Tavassoly, I., Goldfarb, J., & Iyengar, R. (2018). Systems biology primer: The basic methods and approaches. *Essays in Biochemistry*, *62*(4), 487–500. https://doi.org/10.1042/ebc20180003

Thompson, D. W. (1917). *On Growth and Form*, Cambridge: Cambridge University Press.

Tsing, A. L., Swanson, H., Gan, E., & Bubandt, N. (2017). In *Arts of living on a damaged planet: Ghosts of the anthropocene: Monsters of the anthropocene* (pp. M1–M12). Introduction, University of Minnesota Press.

Turner, J. R., & Baker, R. M. (2019). Complexity theory: An overview with potential applications for the Social Sciences. *Systems*, *7*(1), 4. https://doi.org/10.3390/systems7010004

Turner, J. S. (2010). *The tinkerer's accomplice: How design emerges from life itself*. Harvard University Press.

Turner, J. S. (2012). *Evolutionary Architecture? Some Perspectives From Biological Design*. Architectural Design, 82(2), 28–33.

UN Environment and International Energy Agency (2017): *Towards a zero-emission, efficient, and resilient buildings and construction sector*. Global Status Report 2017

United Nations Environment Programme (2021). *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Nairobi

Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics: Its practice and theory. *Journal of The Royal Society Interface*, *3*(9), 471–482. https://doi.org/10.1098/rsif.2006.0127

Vallas, T., & Courard, L. (2017). Using nature in architecture: Building a living house with mycelium and trees. In *Frontiers of Architectural Research*, *6*(3), 318–328.

Van Wylick, A., Elsacker, E., Yap, L. L., Peeters, E., & de Laet, L. (2022). Mycelium composites and their biodegradability: An exploration on the disintegration of mycelium-based materials in soil. *Construction Technologies and Architecture*. https://doi.org/10.4028/www.scientific.net/cta.1.652

Vandermeer, J., van Noordwijk, M., Anderson, J., Ong, C., & Perfecto, I. (1998). *Global change and multi-species agroecosystems: Concepts and issues*.

Varenne, F. (2013). *The Nature of computational things - Models and simulations in Design and Architecture*, In M.-A. Brayer & F. Migayrou (Eds.), Naturalizing Architecture: ArchiLab 2013, pp. 96–105. Hyx editions.

Werfel, J., Petersen, K., & Nagpal, R. (2014). Designing Collective Behavior in a Termite-Inspired Robot Construction Team. *Science (New York, N.Y.)*, *343*, 754–758. https://doi.org/10.1126/science.177.4047.393

Wisselink, M., Aanen, D. K., & van 't Padje, A. (2020). The longevity of colonies of fungus-growing termites and the stability of the symbiosis. *Insects*, 11(8), 527. https://doi.org/10.3390/insects11080527

Yamins, D. (2005). Towards a theory of "local to global" in distributed multi-agent systems (I). *Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems - AAMAS '05*. https://doi.org/10.1145/1082473.1082501

Yusoff, K. (2017). 2017. "Epochal Aesthetics Affectual Infrastructure of the Anthropocene", *Accumulation*. Available at <http://www.e-flux.com/architecture/accumulation/121847/epochal-aesthetics-affectual-infrastructures-of-the-anthropocene/>.

Zak, J. van, Duro-Royo, J., Tai, Y.-J., Ling, A., Bader, C., & Oxman, N. (2018). Parametric Chemistry. In Daas, M., Wit, A. J., (Ed.) *Towards a robotic architecture* (pp. 216–229). Applied Research and Design Publishing, an imprint of ORO Editions.

Exhibition 1

David Andréen
& Ana Goidea

bioDigital matter
Lund University

bioDigital Futures. Technology has so far separated us –the human race– ever further from the natural world. However, seen in another light this divergent trend is not a constant law. On the contrary, development in digital technologies can bring us closer to *nature*, potentially erasing the boundaries that separate biology from technology. Here we seek a radically different future, where principles of self-organization and emergence shape our built environment through cybernetics, organic materiality, and adaptation: the interactive phylogenesis of architecture. In this future, a new relationship with our environment emerges: our cities, industries and communities become part of the ecosystem, giving back as much as they take away.

bioDigital Futures shows a way forward through two pieces, proposing a vision for sustainable architecture. Both pieces explore emerging technologies in 3d printing and computational design within the realm of architecture.

Protomycokion is a column fabricated from a biohybrid material composed of forestry by-products bound together not by glues or plastics, but by the growth of a fungus. It is 3d printed using bioFDM technology. Through the interaction of self-organizing code, design intent, biological agency, and the printing process, a complex form emerges. The column is grown as a living system and retains the flowing, connective nature of such a system. Its appearance emphasises its dual origin, of organic and mechanic nature.

The second piece, *Meristem Wall*, is a section of a building envelope, fabricated through binder-jet sand 3d printing. The wall is fully functional integrating lighting and electricity, utility pipes, windows, and a custom cnc-knitted textile interior surface. However, the functional aspects of the wall go beyond the mundane. Its geometry allows for the channels to be activated through transient flows of air, enabling selective transport of heat and moisture. The flows are controlled through an embedded system of sensors and actuators. The outer parts of the wall shift the channels to a nested landscape of intertwined surfaces, providing an extensive biological habitat in the building itself. The Meristem Wall is a critique of the binary and absolute boundary between human and environment favoured by modernist engineering.

Together these proposals point in a direction of human development where we can reconnect with our surrounding ecosystem and reverse the trend of runaway exploitation. Through the means of digital technologies, the principles of biology can enable an innovative use of new materials, interaction and collaboration with living agents, and enrich the biodiversity of our cities and communities.

Acknowledgements: The project is supported by a grant awarded by the Swedish National Board of Housing, Building and Planning. Several individuals contributed to the projects: Mariana Popescu of ETH Zürich contributed to design and fabrication of the cnc knitted membrane; Dimitrios Floudas of Lund University contributed to the making of Protomycokion; Anton T. Johansson of Lund University contributed to the programming of the Meristem Wall. Fabrication and post-processing of the Meristem Wall thanks to Voxeljet and Sandhelden.

Protomycokion
Photo by: Ana Goidea, 2020

Protomycokion
Photo by: David Andréen, 2020

Meristem Wall
Photo by: David Andréen, 2020

Fig. 19. Time, Space, Existence exhibition vernissage. Photo by Andréen, 2021.

Fig. 20. Opposite page: Protomycokion at Time, Space, Existence exhibition, in Palazzo Bembo.

Exhibition 2

xenoikos. hidden worlds

xenoikos. hidden worlds was a solo exhibition hosted at Spark gallery in Malmö, in 2020. It consisted of Protomycokion, a mirror above it, a poem, a speaker and a projected movie on a fragmented canvas. A light source was integrated within the column, and visible through a transparent section in the middle of the column. The column had audio sensors and modulated the frequency of the light inside the column based on the audio input of both the people around it, as well as the input of the soundtrack. The video was made of several timelapse videography shorts of fungal growth, some visible with the naked eye, some done through a microscope. The soundtrack of the video was made by converting electrical inputs from fungal fruitbodies into sounds, created by artist Michael Prime and reproduced with permission. On the next page is the poem presented in the exhibition.

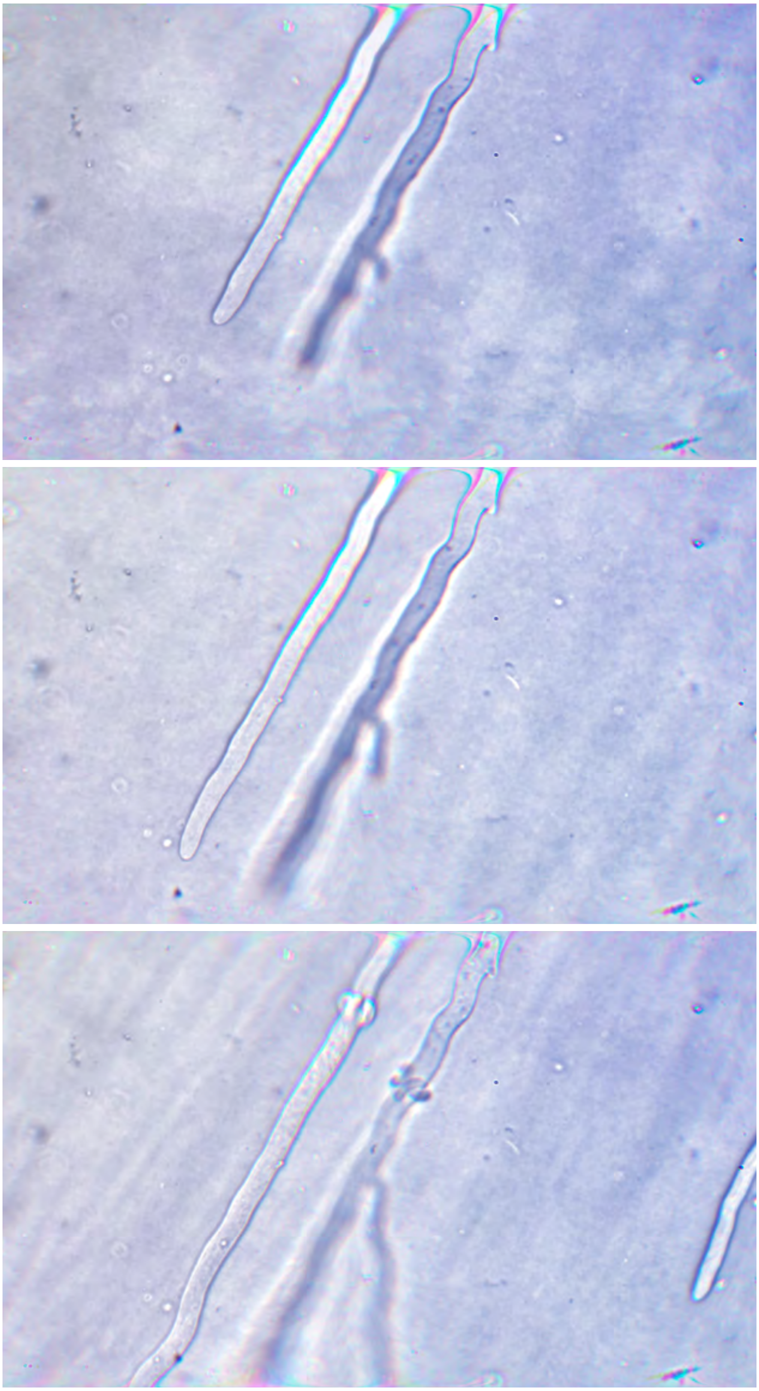


Fig. 21. Opposite page: xenoikos vernissage seen through the window of the gallery. Photo by Andréen, 2020.

Fig. 22. Left: Timelapse photography of fungal growth.

Fig. 23. Below: Protomycokion in front of ungal growth timelapse projection during exhibition.

Fig. 24. Next page: Close-up of Protomycokion. Photo by Andréen, 2021. Andréen, 2020.

What if our homes were alive? What if our walls were breathing? And pulsating and slowly moving? What if that was not something to be corrected? What if that is already happening? And what if it has always been? What if our world is made of many other worlds, and those are brimming with life that is made of other smaller worlds? What if we can't separate between us and them? Are we made of more than human and bacteria? Do those bacteria think on their own? Do they even like us? Are they a collective? Are we individuals? Are we clean? What is clean? Is the desert clean? Is your tap water clean?

Do we think on our own? Is the bacterium that lives on your skin and falls off on your bedroom floor still you? Since you are not you without air in your lungs, does that mean that you are also air?

Can you tell a story without another story? Which story do you believe in? Does anything organize itself? Is anything making itself? Are we familiar with our homes? With our bodies? Why do our rooms have corners? Should walls be straight?

Is culture a product of nature? Are cities part of nature? Are we nature? Or are we different and special? Should we be prioritized? Is our world someone else's? Do eagles have their own world? What about chicken? What about chicken with no legs? Do they live in our world?

Is the unit the individual or the gene? Or is it the species? Are we competing against each other? Do we need to be? Is there enough for all of us? Are we claiming too much? How much is too much? Where did it all start to go wrong?

What does it mean to care for another? Who do we welcome in our homes? How are we choosing who to exclude? Are you influenced by your environment? Are you influenced by hidden things? Do you influence hidden things? How can you tell? Does it matter if you don't see it?

What if we gave in to entanglements instead of enforcing divisions? Can we change how we position ourselves? Can we undo the harm? Can we stop the future harm? If we can, will we?

Do you like mushrooms? Do you eat them raw? Have you ever seen their roots? Do you like the smell of a humid forest floor? Do you know what makes it smell like that?

If you read that "There are more genes in the microbes in your gut than stars in our galaxy", how would that make you feel? Do you think, like I do, that multiplicities are wonderful? Have you ever thought of the heart of an oyster?

Additional information

Paper 1. Goidea A., Floudas D. and Andréen D. (2020). Pulp Faction: 3D Printed Material Assemblies Through Microbial Biotransformation. *Fabricate 2020: Making Resilient Architecture*. Edited by Burry, J., Sabin, J., Sheil, B., & Skavara, M. UCL Press, London, pp. 42-49.

Presented at and published in Fabricate 2020, a leading European peer-reviewed triennial conference and book published by UCL Press (Scientific level 1 at the Norwegian register for scientific journals, series, and publishers) on digital fabrication in the architecture and construction sector. (The presentation was one of 20 live presentations and 32 projects featured in the book out of 220 submissions. The transmissions of Fabricate 2020 count over 8,000 views from 100 countries across the globe, and the book has been downloaded over 55 000 times as of 17th of January 2023.)

The paper was awarded for "Most forward-thinking research", and has been cited 39 times (Google Scholar 2023-09-19).

Paper 2. Goidea A., Floudas D. and Andréen D. (2022). Transcalar Design: An Approach to Biodesign in the Built Environment. *Infrastructures*, 7(4):50.

This paper was published in the MDPI journal "Infrastructures" (H-index 23, SJR; Scientific level 1 at the Norwegian register for scientific journals, series, and publishers), special issue Selected Papers from CEES 2021, the first International Conference on Construction, Energy, Environment and Sustainability (Coimbra, 2021), on the topic of Sustainable Construction Materials and Technologies, where it was presented in the thematic session TS15: Responsible biotechnologies and biodesign for the built environment.

A slightly different (due to the additional and independent peer-review of the journal) version of the paper was also published in the conference proceedings.

The paper has been cited 8 times (Google Scholar 2023-09-19), and has been accessed 2390 times (mdpi.com, 2023-09-19).

Paper 3. Andréen D. and Goidea A. (2022). Principles of biological design as a model for biodesign and biofabrication in architecture. *Architecture. Structures. Construction*, 2, pp 481–491.

This paper was published in Springer journal “Architecture, Structures and Construction” (Scientific level 1 at the Norwegian register for scientific journals, series, and publishers) special issue Structures & Architecture: Joining Forces, which features a number of select papers from the International Conference on Structures and Architecture in Aalborg in 2022, where the paper was presented at the mini symposium Biodesign: New material practices for a sustainable building culture. The paper is also present in the conference proceedings as an extended abstract.

The paper has been cited 4 times (Google Scholar, 2023-09-19) and accessed 3717 times (springer.com, 2023-09-1)

Paper 4. Goidea A., Popescu M. and Andréen D. (2021). Meristem Wall an exploration of 3d printed architecture. *ACADIA 2021. Realignments: Toward Critical Computation.* Edited by B. Bogosian, K. Dörfler, B. Farahi, J. Garcia del Castillo y López, J. Grant, V. Noel, S. Parascho, & J. Scott. pp. 438-443.

Published in Realignments: Toward Critical Computation, the Proceedings of the 41st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA).

The paper was awarded runner-up in the category “Best Project”, and has been cited once (Google Scholar 2023-09-19).

Paper 6. Andréen D., Goidea A., Johansson A. and Hildorsson E. (2019). Swarm Materialization Through Discrete, Nonsequential Additive Fabrication. *IEEE 4th International Workshops on Foundations and Applications of Self* Systems (FAS*W)*, Umea, Sweden, pp. 225-230.

This peer-reviewed paper was published in the conference proceeding for 2019 IEEE 4th International Workshops on Foundations and Applications of Self* Systems (FAS*W) (Scientific level 1 at the Norwegian register for scientific journals, series, and publishers), after a presentation at the 3rd International Workshop on Self-Organised Construction (SOCO).

The paper has been cited once, and has 123 full text downloads (IEEE.org 2023-09-19).

Exhibition 1. bioDigital Futures.
Exhibition period: 22 May 2021 - 21 November 2021
Venue: Palazzo Bembo Venice, Italy
Organizer: European Cultural Centre - Italy
https://ecc-italy.eu/exhibitions/2021architecture

bioDigital Futures. Andréen, D. and Goidea, A. (2021). Venice, Italy. May-October 2021. Pedrana, Lucia De Stefano, Rachele and Valeria Romagnini, eds. *Time Space Existence, European Cultural Centre*. Published following the exhibition Time Space Existence at Palazzo Mora, Palazzo Bembo and Giardini Marinaressa, Venice, Italy.

bioDigital Futures exhibition was awarded a Special Mention as runner-up in the Design Innovation category.

Exhibition 2. **x**enoikos. hidden worlds.
Exhibition period: 30 October 2020 - 22 November 2020
Venue: SPARK Gallery, Malmö Sweden
Organizers: Anna Lavén, Max Gerthel, Per-Johan Dahl
https://www.sparkmalmo.org/exhibitions

Figures

Fig 1. By the author.

Fig 2. Heim, M., Römer, L., & Scheibel, T. (2010). Hierarchical structures made of proteins. The complex architecture of spider webs and their constituent silk proteins. Chemical Society Reviews, 39(1), 156–164. https://doi.org/10.1039/b813273a. [Diagram]. Reprinted with permission.

Fig 3. Noronha, A., Modamio, J., Jarosz, Y., Guerard, E., Sompairac, N., Preciat, G., Daníelsdóttir, A. D., Krecke, M., Merten, D., Haraldsdóttir, H. S., Heinken, A., Heirendt, L., Magnúsdóttir, S., Ravcheev, D. A., Sahoo, S., Gawron, P., Friscioni, L., Garcia, B., Prendergast, M., … Thiele, I. (2018). The Virtual Metabolic Human database: integrating human and gut microbiome metabolism with nutrition and disease. Nucleic Acids Research, 47(D1). https://doi.org/10.1093/nar/gky992 https://www.vmh.life/#reconmap (CC BY-NC ND 4.0)

Fig 4. Nicholas, P., Zwierzycki, M., Stasiuk, D., Norgaard, E., & Thomsen, M. R. (2016). Concepts and Methodologies for Multiscale Modeling: A Mesh-Based Approach for Bi-Directional Information Flows. ACADIA Proceedings. https://doi.org/10.52842/conf.acadia.2016.308. [Diagram]. (CC BY-NC)

Fig 5. BIO EX-MACHINA. Biological meets Digital Computing & Robotics [Photograph]. https://www.corpuscoli.com/projects/bio-ex-machina/. © Officina Corpuscoli / Maurizio Montalti. Reprinted with permission.

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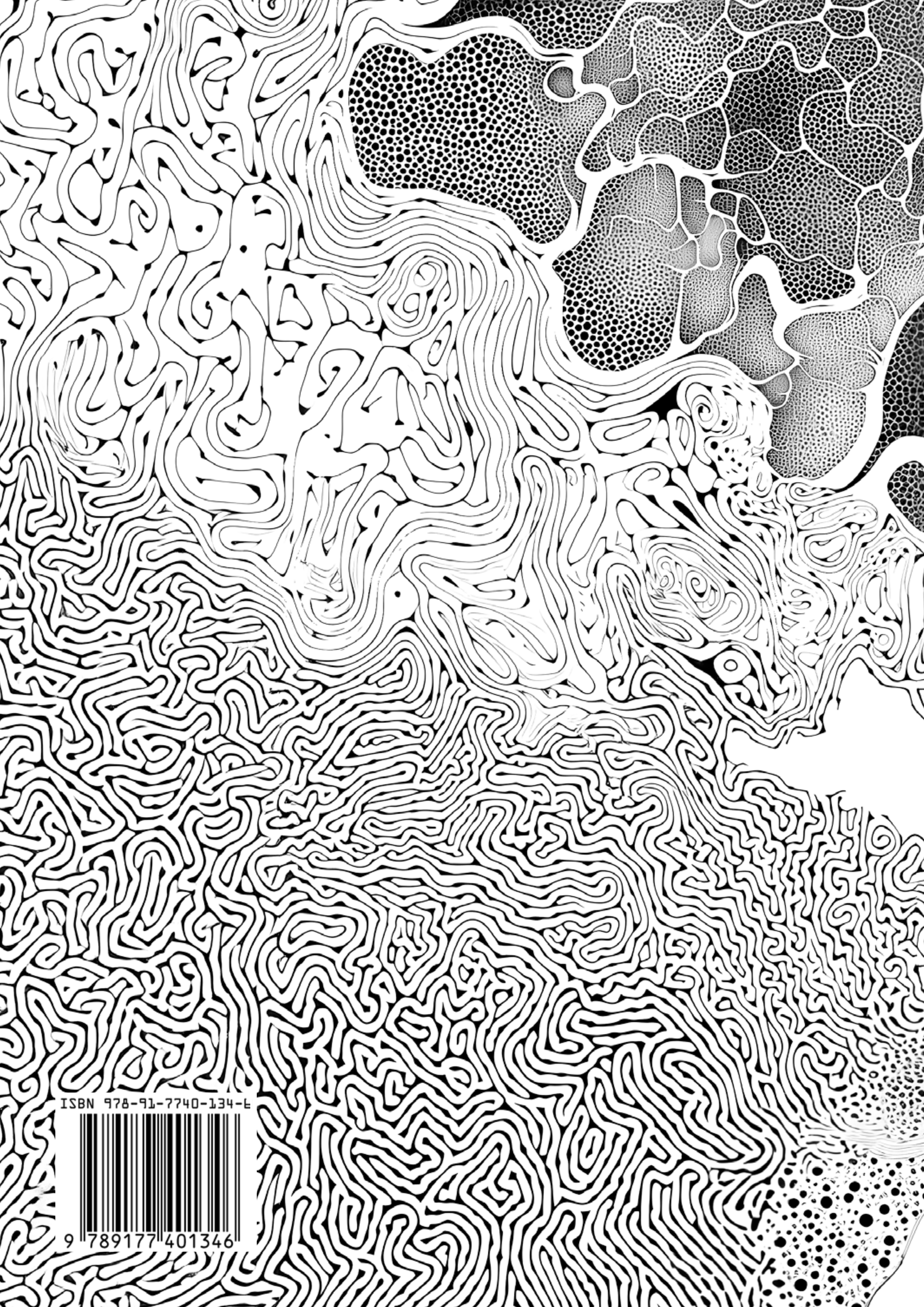

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