MICROBIAL MATERIALS IN ARCHITECTURAL PRACTICE

A three-dimensional approach to the future of biocement and mycelium composites as construction materials

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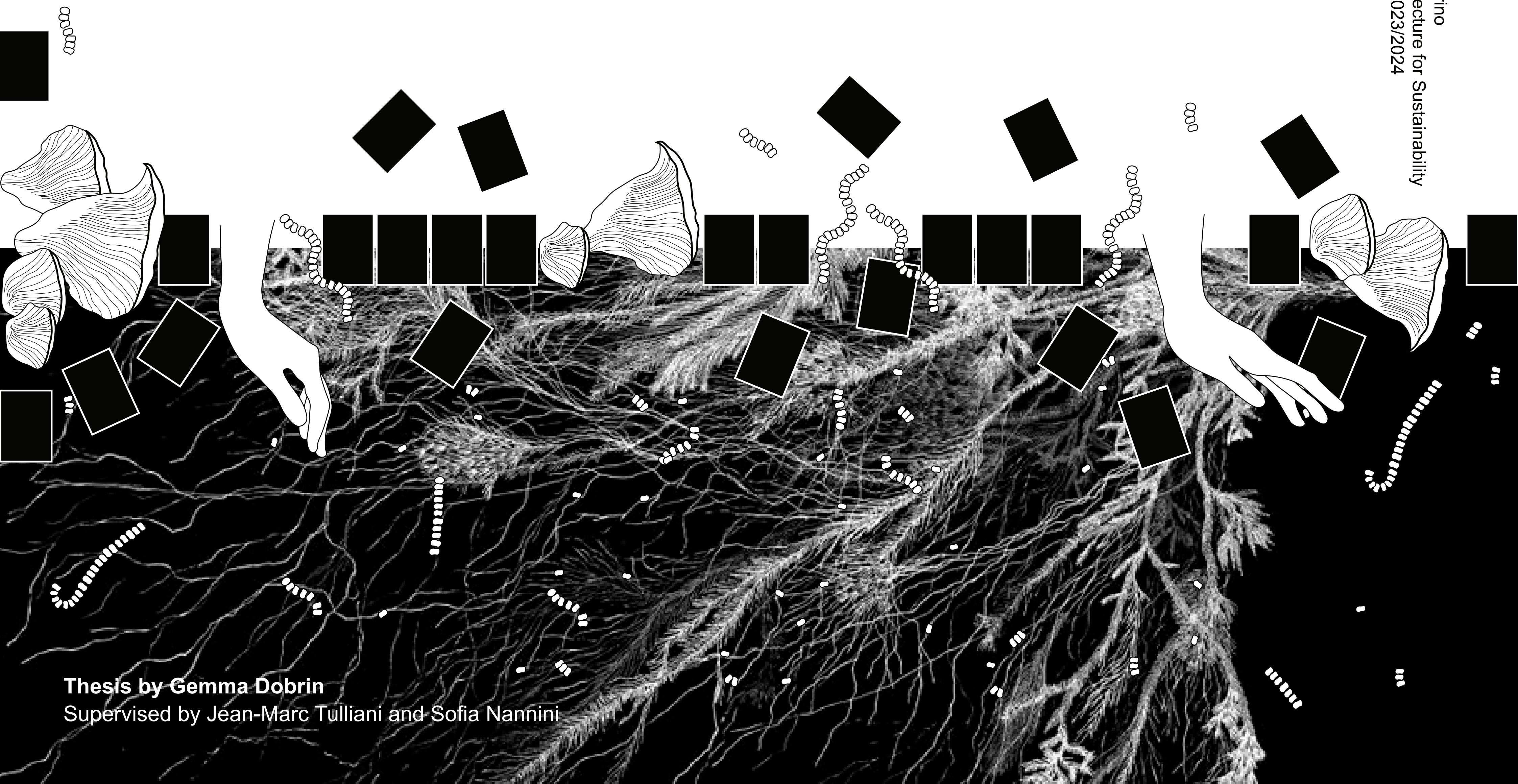

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Abstract

This thesis investigates biocement and mycelium composites as building materials for their viability to be integrated into an existing framework, as well as their capacity to challenge traditional notions of architecture and sustainability.

The research explores a three-dimensional approach to imagining a future with these materials by analysing specific biocement and mycelium composite products from three perspectives:

1. Technical performance and material properties in comparison to conventional materials
2. Environmental implications considering resource depletion, end-of-life scenarios, and carbon emissions
3. A more complex theoretical investigation into interspecies ethics and shifting paradigms through historical narratives and case studies

While a technical comparison assesses the viability of biocement and mycelium composite products in comparison to conventional building materials, and an environmental analysis assesses the benefits and necessity for considering their integration, it is ultimately the overlaying of these dimensions, while addressing the critical ethical considerations they inspire, that differentiates this study. The heart of this lies in shifting narratives away from a human-centric perspective, to recognise and appreciate the agency of non-human life forms as actors in the production process as explained and influenced by these materials.

This theoretical investigation culminates in the application of this three-dimensional approach to addressing the challenges facing the widespread implementation of biocement and mycelium composites in architectural practice. Through this practical application, we can see some of the ways in which interspecies collaboration in material production can inspire and pave new pathways for a more sustainable future for architecture.

Key words: *biocement, mycelium composites, architectural practice, sustainability, three-dimensional, technical, environmental, interspecies ethics, microorganisms*

Contents

1. THE PREFACE

Introducing the topic, aims, questions and research methodology

1.1. Introduction

Over history, humans have had an evolving yet troublesome relationship with nature, governed by rationalisation, power and control. This has laid the foundation for the unsustainable growth of modern society through mass extraction and production practices, which has contributed substantially to the current environmental crisis we now find ourselves in. Modern architecture and construction industries represent this through design typologies that frame nature as a resource or an ‘other’, and quick, cheap materials that enable rapid development whilst extracting, consuming and emitting at a rate that causes serious environmental implications such as climate change, resource depletion, health issues and loss of biodiversity. It is therefore critical to address the sustainability of architecture and construction, as well as working on mending our relationship with nature in order to work towards a more sustainable and healthy future, for both ourselves and the planet.

This is where materials such as biocement and mycelium composites become useful tools. These materials, which are dependent on the metabolism and agency of microorganisms, offer opportunities for more environmentally friendly architectural practice through material production, while simultaneously enabling us to explore the collaboration with more-than-human entities and learn new pathways for our relationship with non-human nature.

However, bridging the technical and environmental with a more complex theoretical investigation into interspecies ethics is a complex and unprecedented task, yet one that is critical in a holistic approach to sustainable futures. This is precisely the aim of this thesis, to compile an understanding of all three of these dimensions, using biocement and mycelium composite products as case studies, and tackle the task of overlaying them to pave a new future for sustainable materials in architectural practice.

Aims and objectives

In order to achieve the aim of outlining the technical, environmental and interspecies dimensions of biocement and mycelium composites in order to apply a three-dimensional approach to a more sustainable future for architecture, the following objectives were set out:

1. Outline the theoretical framework and relevance of more-than-human, multidisciplinary and multispecies approaches to be integrated with a focus on microorganisms.
2. Conduct a historical analysis of these novel materials in a broader social, scientific and technical context.
3. Examine and compare the technical properties of biocement and mycelium composite materials to evaluate their viability as alternatives to conventional building materials.
4. Analyze the environmental impact of biocement and mycelium composite materials in relation to conventional alternatives.
5. Identify and discuss the ways that biocement and mycelium composite materials shift paradigms in architecture.
6. Explore the multispecies dynamics and ethical implications of the production and use of biocement and mycelium composite materials, focusing on the agency and autonomy of both human and non-human life
7. Explore a future for the integration of biocement and mycelium composites through a three-dimensional approach.

Research questions

The main research questions adressed through this thesis include:

1. How has the perception of sustainability and the human-nature relationship evolved over time within the realm of architecture and construction, and what role do biocement and mycelium composites play in this narrative?
2. How do biocement and mycelium composites perform technically and environmentally in comparison to conventional construction materials? i.e. are they viable alternatives and for what applications?
3. What multispecies ethical considerations arise from the historical and current use of microorganisms, particularly in architectural materials, and how can these inform more conscious production practices?
4. How can this way of thinking about production, fostered by multispecies collaboration, reshape architectural practices?
5. What challenges are facing biocement and mycelium composite in terms of integration and scalability, and how can they be addressed in the practical, ethical and environmentally sustainable integration of biocement and mycelium composites as construction materials?

Hypothesis

I hypothesise that materials produced in collaboration with microorganisms for architecture, specifically biocement and mycelium composites, offer not only environmentally sustainable alternatives to conventional materials, but also foster environments for re-imagining the interspecies ethics of architecture and material production that consider the agency of both human and non-human actors. These materials therefore have the ability to set up a basis for shifting paradigms in architecture and design practices, as well as offering technical solutions to environmental challenges.

1.2. **Methodology**

This thesis as a whole follows a mixed methods research methodology, and ultimately aims to combine both a quantitative and qualitative analysis of biocement and mycelium viewed as novel, sustainable alternatives to construction materials which are reliant on the metabolism and agency of microorganisms. The challenge of this work is in bringing together these approaches to form a more complex understanding of these materials, their contexts, futures and the conversations they facilitate within this framework.

The setting - Qualitative

The aim of the first section is to contextualise biocement and mycelium composite building materials within shifting perceptions of sustainability, microbial agency, and the relationships between humans and nature. By situating these materials within a narrative of evolving perspectives, the aim is to provide a foundation for discussing biocement and mycelium composites beyond their technical attributes, fostering more complex questioning regarding their role in sustainable architecture.

The methodology for this section will be primarily qualitative, focused on the understanding of the broader framework within which biocement and mycelium products emerged and the conversations they foster regarding the future of sustainable architecture and building materials.

I hypothesise that a deeper understanding of the historical context of the emergence of biocement and mycelium composites in reference to changing perspectives of microorganisms, sustainability, human-nature relationships and more-than-human agency, particularly when overlayed with the subsequent quantitative analysis, will facilitate a deeper level of questioning and conversation regarding the future scaling of these materials. This research will utilise case studies as a tool for visualising and understanding applications of the ideas discussed.

The research was conducted as follows:

1. Literature immersion and review:
To situate biocement and mycelium composite materials within a comprehensive historical and theoretical context, literature in the form of primary sources, historical books, scholarly articles and reports was collected and reviewed across fields of architecture, design, medicine, chemistry and social sciences in relation to the historical evolution and theories of sustainability, use of microorganisms, the relationships between humans and nature and more-than-human perspectives.

2. Case study identification and examination:
Similarly, case studies relevant to the themes addressed through the literature review were identified and examined. Case studies support a visual and practical understanding of how these themes manifested through human activity over the course of history.

3. Timeline development:
The data collected through literature review and case study was collected in chronological order to connect events and perspectives across disciplines over time. This method helps to bridge the gap between narratives from different disciplines in order to identify the themes which are most prevalent across a range of existing material.

4. Theme development:
Themes were identified through a cross disciplinary timeline analysis in relation to the aim of situating biocement and mycelium composite materials in a broader theoretical and historical context. This involved identifying commonalities between narratives of different disciplines including but not limited to architecture, engineering, biology, chemistry and social sciences.

5. Writing up:
The relevant narratives were then written under the themes

identified through the above-mentioned process, with relevant quotes and case studies to illustrate and support the role of the narrative in contextualising the development of materials grown through human-microbe collaboration with a focus on the specific materials of biocement and mycelium composites.

6. Connecting:

Key words and concepts were connected through case study references throughout the body of work so that the interconnected nature of different disciplines and research methodologies can be interfaced.

The aim of the next section is to identify to which conventional building materials each type of microbial material is best suited as an alternative and assess how competitive they could be to conventional materials from a technical and environmental perspective.

I hypothesise that novel microbial materials such as biocement and mycelium composites offer the potential to be competitive alternatives to conventional building materials for structural and insulative applications as well as providing environmental benefits considering resource depletion, end-of-life scenarios, energy use and carbon dioxide emissions. Therefore, a deeper conversation regarding human-nature interactions is warranted to facilitate a holistic approach to the scaling up of these materials.

The methodology for this section will be based on a primarily quantitative approach where the collection of relevant technical data will allow for a comparison and assessment of the current state of application of novel products and projects in relation to conventional products. The data will be collected by analysis of existing data sheets published by producers and sectors.

The research was conducted as follows:

1. Identification and selection of biocement and mycelium composite products and conventional comparisons:

The basis for a successful comparison relies on the identification of relevant products and projects. The selection of relevant biocement and mycelium composied products was based on current availability and applications identified through advertised market products and ongoing use in projects. The selection of comparable conventional materials was based on the most common products that are currently being used for the existing and potential uses of biocement and mycelium composite.

2. Analysis of biocement and mycelium composite production processes:

This involved outlining the production processes from a technical and chemical perspective. To facilitate a connection with the theoretical framework of a more-than-human approach, diagrams will be utilised to visualise each production process with particular attention to the roles of microorganisms and microbial agency.
The diagrams and process descriptions were aimed to illustrate not only the steps involved in production but also the biological interactions that enable the synthesis of these materials.
This is critical in understanding the materials from technical, environmental and more-than-human perspectives.

3. Collection of material property data:

The analysis of suitable comparisons was based on material properties. The data for these properties was collected from existing material data sheets and company websites and publications.

4. Analysis and comparison of material property data:

The data collected in the previous step guided the identification of appropriate applications and comparisons, and commentary on the viability and potentials of biocement and mycelium composite materials. This was done by identifying the highest performing values for each specific property and commenting on the data in relation to other materials and applications. The findings from this analysis structured the subsequent environmental analysis

5. Identification of raw materials and their impact for each material:

For each material the raw materials were identified and commented on regarding their environmental impact with a focus on renewability and resource depletion.

6. Comparison of resource approaches based on identified alternative comparisons:

The relevant comparisons were collected in the form of a table identifying the different approaches to both the shared and unique resources required. Where numerical data is not available, the comparison focused on the specific approach to resources. Diagrams were also used to visualise more intricate resource ecosystems where necessary, with a focus on the role of the microorganism.

7. Identification of end-of-life scenarios for each material:

The end-of-life scenarios for each material were identified under the topics of durability and biodegradability, reuse, recycling and waste management, and toxicity and pollution. This data was collected through analysis of a combination of product data sheets, material safety data sheets, environmental declarations and company websites and publications.

8. Comparison of end-of-life scenario based on identified alternative comparisons:

The findings were collected in a table to summarise the different end-of-life scenarios for each material. This data substantiated the end-of-life and reuse-recovery-recycling potential phases of the following steps.

9. Identification and discussion of energy consumption and carbon emissions for each material:

The key energy requirements and savings were identified for each material in relation to the carbon dioxide emissions or savings, which was the main focus for data collection and analysis. The data for conventional construction materials was collected from environmental product declarations (EPDs). As there are not yet any formalised EPDs or LCAs, the data for biocement and mycelium composite materials was collected from a wider range of sources including company websites and publications, material data sheets, reports and articles.

10. Comparison of energy consumption and carbon emissions based on identified alternative comparisons:

The data collected informed diagrams and tables to facilitate a comparison of relevant alternatives in their approach to carbon footprint throughout the phases outlined by the life-cycle-approach. The tabulated information took a relative comparison approach as the same level of data was not available for novel materials as there is for existing ones.

11. Concluding remarks:

Commentary was made based on the data analysis and comparison in order to conclude the findings in relation to the research aim and hypothesis.

The future - Qualitative

The aim for the final chapter of the thesis is to overlay the three-dimensions explored through the work so far to identify key themes and considerations to apply to paving a future for the integration of biocement and mycelium composites which fosters more collaborative architectural practices from a more-than-human perspective.

The methodology for this section is a qualitative reflection and future speculation, drawing from the narratives, case studies and specific material investigations of the preceding chapters. This methodology aims to address the connection of the three-dimensions, the main challenge of the work. In order to aid this, this section will help clarify the third dimension by identifying key words and themes to synthesise the research conducted. Then, by adressing the challenges facing the implementation and scaling of biocement and mycelium composites, this section provides the possibility to test the methodology through practical examples, integrating all three-dimensions to speculate a path forward. This was conducted as follows:

1. Identification of key words phrases

Reflecting on the body of work conducted across the three dimensions, key words and phrases were identified as integral to the narratives explored. The key words were then elaborated on in reference to their roll in the narrative and context of the research. This aims to identify the key themes brought up through the narrative of the research, to begin overlaying and connecting the three-dimensions represented.

2. Thematic mapping to identify key themes for paradigm shifts

The key words were mapped according to their relevance in architectural practice and microbial interactions in order to understand the key themes they address in terms of paradigm shifts which are brought up through the three-dimensional investigation.

3. Elaboration and exploration of paradigm shifts

Each of these themes, or paradigm shifts, were explored in more detail in relation to the specific materials and relations they address through commentary and visualisations.

4. Identification of challenges facing implementation and upscaling of materials

To apply this three-dimensional approach to the future of biocement and mycelium composites as construction materials, the challenges facing the implementation and upscaling of these materials was identified through a SWOT analysis of each specific material.

5. Responding to challenges through a three-dimensional perspective

The main challenges identified in the previous step was elaborated on in reference to the key words and key themes/ paradigm shifts discussed previously. This methodology fosters a three-dimensional analysis by enabling a complex set of relations to be applied to practical applications, allowing for the overlaying of this with the technical and environmental knowledge from the respective analyses. This is the main challenge of the work, however this methodology helps to clarify the third dimension as well as providing the framework to test the methodology. To aid the discussion, tools including examples, diagrams and drawings were used to support the commentary.

6. Synthesis of information

Finally, the key points from the application of this approach to a practical example were summarised to highlight the key challenges, strategies and considerations facing biocement and mycelium composites within a complex, multi-dimensional context.

1.3. **Glossary**

Bacteria
Bacteria are microscopic living organisms composed of only one cell. Bacteria are critical to healthy functioning of humans, as well as ecosystems, however the relatively small number of species cause disease have caused the human perception of their relationship to be governed by fear, control and division. Some bacteria also possess the ability to precipitate calcium carbonate through Microbially-Induced Calcium Carbonate Precipitation (MICP), which enables the production of biocement.

Biocement
Biocement, in this case, encompasses cementitious materials that are supported by the metabolism of microorganisms, which offer an alternative to portland cement-based products. Biocement refers to the calcium carbonate precipitated by microorganisms through the biomineralisation process known as MICP, which has the ability to replace portland cement as a binder to create concrete-like products as well as autonomously healing cracks in new and existing concrete structures.

Cyanobacteria
Also known as blue-green microalgae, cyanobacteria are a division of microorganisms that are capable of photosynthesis. These organisms are also able to precipitate calcium carbonate and assist in the production of biocement.

Microorganism
Microorganisms encompass a diverse range of microscopic living organism including bacteria, viruses, fungi, and some algae. Microorganisms are found almost everywhere and play essential roles in ecosystems and nutrient cycles. They perform metabolic processes, which humans are discovering to be useful in relation to our own mechanisms through health, production, agriculture and more.

Microbial agency
Microbial agency refers to the idea that microorganisms possess agency and can influence ecological, social and now production processes. This concept emphasises the role of microbes in shaping environments, human health, and now will be explored through their agency in material production.

Microbially-Induced Calcium Carbonate Precipitation (MICP)
A result of metabolic interactions between microbial communities and organic and/or inorganic compounds present in the environment whereby calcium carbonate is formed as a product (Castro-Alonso, et al., 2019). MICP serves as the basis for the biomineralisation in biocement materials. The metabolic processes of MICP that are utilised in the production of biocement in these case studies refer mainly to urea hydrolysis and photosynthesis.

More-than-human theory
More-than-human theory challenges anthropocentric views by recognising the agency and significance of non-human entities. It emphasises the interconnectedness of human and non-human actors in ecosystems, advocating for a broader understanding of relationships beyond human-centered perspectives.

Mycelium
Mycelium is the root-like structure of fungi, consisting of a network of thread-like structures called hyphae. Mycelium plays an important role in forest ecosystems as well as natural decomposition processes and has the ability through its structure and metabolism to process and bind organic (and inorganic) matter into composite materials.

Mycelium composite
Mycelium composites are materials made by binding a substrate, often organic waste, with mycelium, resulting in biodegradable materials with potential applications in construction, packaging, and insulation.

2. THE SETTING

Situating materials in historical and contextual framework through tracking human and nature relations

The following historical narratives aim to contextualise biocement and mycelium composites as building materials within shifting perceptions of sustainability, microbial agency, and the relationships between humans and nature. By situating these materials within a narrative of evolving perspectives, the aim is to provide a foundation for discussing biocement and mycelium composites beyond their technical and environmental attributes, fostering more complex questioning regarding their role in sustainable architecture.

Through the course of history, the attitude towards nature as a whole, and microorganisms in particular, has been constantly shifting through varying degrees of classification, organisation and control, ultimately leading, coupled with climate anxiety, to the current context of social, design, technological and architectural aspirations and practices. In this collection of histories, to borrow the words of Bruno Latour, I aim to “use history as a brain scientist uses a rat, cutting through it in order to follow the mechanisms that may allow me to understand at once the content of a science and its context” (Latour, 1988, p. 12). Through this approach, I hope to able to move forward with a technical yet deeply contextually grounded study of the current uses of microbes in architectural building materials; namely biocement and mycelium composites.

This however, I am not expecting to be a simple task, as it requires me, the architect, to sit at a midpoint between scientific, technological and biological specificities and their intricate social contexts. This position requires an understanding and narrating of a specialised yet multidisciplinary knowledge. Charlotte Brives and Alexis Zimmer reiterate however, that it is exactly this highly interdisciplinary nature of the field research linking the social sciences and microbes in particular that makes it so difficult and complex, and therefore under-represented. They explain further that “an understanding of social and biological dimensions requires the sharing of onto-epistemological methods and approaches specific to each discipline, often requiring sustained efforts in translation, articulation and diplomacy" (Brives & Zimmer, 2021). Although challenging, an appreciation for the importance of such interdisciplinary practice and research is growing as we try tackle the immediate challenges of the climate crisis on a deeper level. As we find ourselves in an existential crisis situated in a proposed epoch of the Anthropocene, whereby we are so prominently seeing the implications of our actions on the core environmental metabolisms our only natural home, people are exploring every avenue to mend, engineer or even escape the storm. In the field of architecture, I believe it is rather a shift in the way we approach the making of materials and our habitat, taking into account the mistakes made over the course of history across multiple disciplines, rather than a specific material solution that will ultimately help repair a damaged human-nature relationship, and may offer a glimmer of hope for a collaborative future on Earth. It is for this reason, that a glance to the past can help us understand how to re-imagine our practices and methodologies to be more mindful of non-human entities and their role in healthy social and environmental ecosystem functioning.

Humans have been interacting with what we define as "nature" since the beginning of our time. Before the conception of the 'modern human', it is understood that belief systems such as Organicism held nature in intimate relationship with humans (St. Pierre , 2019, p. 93). However, through our quest for rationalism, growth and power, not only have our beliefs and resulting actions manipulated our relationship with nature but have also manipulated the natural world irreversibly on a physical level. Similarly, although the first recorded accounts of human use of microorganisms dates back to an Egyptian stela from 2300BC, showing stages of the brewing process (Bud, 1993, p. 2), in a study of the history of the current uses of life, or 'biotechnology' as we know today, it may be wrong to date this history so far back. Therefore, in this framework I will explore the history of the modern human, in a time that rationalising and recording knowledge became an integral part of Western human culture. This 'continuum of changes' that continues to shape design in Western society, as articulated by Louise St. Pierre in a chapter of the book *Design and Nature: a Partnership*, edited along with Kate Fletcher and Mathilda Tham, entitled "Design and Nature: a History", was catalysed by the Scientific revolution of the 1500s (St. Pierre , 2019, p. 93). These changes represent the beginning of rational anthropocentrism, whereby the hegemony of human male intelligence implies that humans are the only species able to reason, backgrounding women, non-Western cultures and the other, as well as diminishing society's ability to see mystery and enchantment in the natural world (St. Pierre , 2019, p. 94).

The boundaries of historical studies are limited to the availability, collection and recording of information, therefore, are too primarily centered around a Western perspective. It is critical to be aware of this shortcoming, and not take these accounts to be the only story of history, or the only way of understanding this human-nature relationship. However, with this in mind, it could be said that it is nevertheless the Western capitalist society that is a primary contributor to climate change, through rapid industrial development and the construction industry coupled with a broken relationship with nature, and therefore it may be useful to look back on this specific history to learn from our own mistakes.

It is also important to recognise one's own biases, that I, although having grown up in South Africa, a colorful and diverse country with a complicated and painful past, have been privileged in my upbringing and opportunities granted to me with the side effect of unfair social relations. Therefore, although I do not claim to be able to provide an all-encompassing perspective, I hope to be able to trace the impact of Western perspectives on the planet, keeping in mind that this is not the only story to be told.

2.1. Historical overview: **Shifting perceptions of sustainability & design**

Timeline: *1800s - 2024*

The changes and technical advancement brought about during the scientific revolution symbolised a transition in human belief systems in relation to how we understand the world and interact within it. General tendencies across disciplines changed from understanding ourselves within a world governed by magic and mystery to one characterised by a growing belief in the ability of the sciences to measure and rationalise. In this transition, the growing belief in rationalism brought about through science, gave the highest value to male intelligence, and as a result women, non-western cultures, non-human beings, all forms of 'other', gradually became further and further backgrounded. This tendency can be recognised for its role in colonial histories and the dominance of Western culture still prevalent today.

Similar beliefs were expressed in developments in art, philosophy, and politics through the Enlightenment period, which carried through the celebration of reason as the power by which humans understand the universe and improve their own condition, however ultimately it was this exact expression of excess that leaded to its own demise.

The following Romantic period, of the late eighteenth to mid-nineteenth century, sprouted as an intellectual orientation in response, to some extent, against the ideals of the Enlightenment, and rationalism in general, rather favoring again the irrational and transcendental.

Louise St. Pierre argues that "the Scientific Revolution, the Enlightenment and the elevation of scientific and rational thinking combined to diminish society's ability to see mystery and enchantment in the natural world. This became apparent in the way that "Westerners no longer saw themselves within an unbounded and uncontrollable cosmos, a world that was larger than humans, a magical world of intrinsic value" (St. Pierre , 2019, p. 94). This notion of control is a crucial theme in the changing human-nature relationships, and something that still continues to shape this relationship. With the power of science now in their hands, humanity during this time began to feel the possibility to control the previously uncontrollable and rationalise what was previously understood as magical, resulting in an inflation of the power of the human (male) self, and the diminishing of the power of the other, that which is separate and distinct from the rational man.

Ecology and ecological design *(1860s – World War II)*

Following in the footsteps of Romanticists, artists, designers and philosophers in the mid-late 19th century, led by William Morris, the Arts and Crafts Movement[1] emerged as a rejection to rationalism and the mechanist thinking of the preceding period. With this came an ideal to return to the mysticism of nature, envisioning a world where humans are integrated with nature.

Similarly, there were other design movements which emerged through this rejection of mechanisation and industrialisation. Designers of the Art Nouveau[2] movement took these principles even further in terms of aesthetic emulation of natural forms manifesting in an architecture characterised by organic, flowing lines and intricate designs with an emphasis on beauty as inspired by nature.

However, in reflection it can be observed that these ideals physically manifested on a superficial level through a stylistic emulation in human-centric and commercial applications rather than for intrinsic concern for integration. Through this decontextualisation of natural forms and systems, nature remained an 'other', to be used for mankind's pleasure or manipulation, a story to foreshadow the following explorations of ecological design (St. Pierre , 2019, p. 95).

1
See case study: *Red House*
William Morris & Philip Webb
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2
See case study: *Tassel House*
Victor Horta
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William Morris & Philip Webb – Red House

Key words: *Rationalist rejection, romanticism, craftsmanship*

01.

The Red House was commissioned by William Morris and designed by architect Philip Webb in 1859 in the peak of the Arts and Crafts Movement. The house is representative of the attempt to reject rationalist and mechanist thinking through a design language which is more romantic.

Red House was designed to harmonise with its natural surroundings, an asymmetrical design and natural materials, blending into the landscape to foster a perception of being part of the environment rather than imposing upon it.

Reflecting the emphasis on craftsmanship adopted by designers of the Arts and Crafts Movement, the house is adorned with handmade details, from furniture to stained glass. This human touch was believed to foster a deeper, more meaningful connection between people and their surroundings. The images represented in the interior embellishments are inspired by natural patterns.

Figure 01. *Red House ceiling decoration:* nature-inspired ceiling motif of Red House gives ‘human touch’ to foster connection between people and surroundings

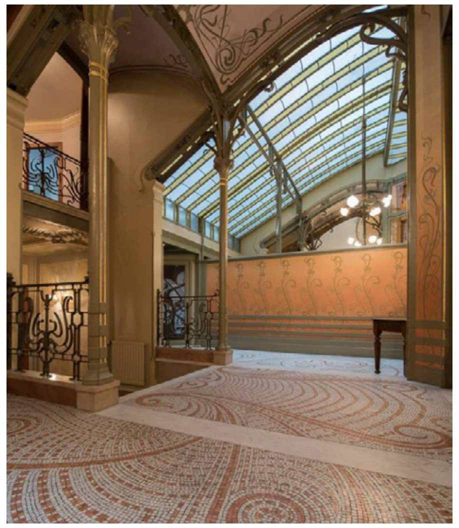
Figure 02. *Red House exterior:* view from external garden showcasing connection between built form and landscape

02.

Victor Horta – Tassel House

Key words: *Art Nouveau, decorative, iron, organic pattern*

03.



Commissioned by its owner Emile Tassel in 1893, Tassel House is the first architectural work representative of the key principles and aesthetics of Art Nouveau.

Inspiration from nature is integrated into the structure through decoration replicating natural forms. Although born from a rejection of industrialisation, a key element in the design was the implementation of iron as a structural and decorative material, only made possible by developments of the industrial revolution.

The staircase has become an iconic example of this type of interpretation of nature, with light iron balustrades showcasing flowing, organic patterns. These motifs are emulated throughout the interiors.

Figure 03. *Tassel House interior:* embellished with organic decorative elements from floor to ceiling

Figure 04. *Tassel House staircase:* the iconic staircase with decorative balustrade made possible with developments in iron production

04.

Along with developments in steel and iron, concrete made from portland cement as developed in the mid-1800s grew in dominance as a construction material in the latter half of the nineteenth century. The material enabled large scale construction such as metros and subways, which grew with the expansion of cities with booming economic development. By the end of the 1800s, concrete also became a mainstream material for housing construction (Nobis, 2021). As studied in depth by Adrian Forty in *Concrete and Culture: A Material History* (2012), concrete's versatility and strength liberated design from structural constraints, which ultimately began to define a new architectural language.

At the turn of the 20th century, ecological thinking was seen as a new way of looking at the world (St. Pierre , 2019, p. 95). While at the time it was seen as closer to an Organicist way of understanding the world and reconnecting with the mystery of nature, contrarily, ecological design as a practice was expressed as a way of controlling and organising nature or society. Following the footsteps of 19th century biology which witnessed a switch from historical examination to experimental investigation, the historian of science William Colemen argues that design has introduced to ecology the meddling with natural systems, either by imitation, replication, regulation, or speculative representation (Coleman, 1978). Ecological design as mastery, as St. Pierre points out, therefore grew out of the conception that humans can be entirely separate from nature and can control natural systems (St. Pierre , 2019, p. 96), a concept eerily echoing believes developed during the Scientific Revolution and the Enlightenment.

Haeckel's definition of ecology, as well as Charles Darwin's Theory of Evolution were also incredibly influential in the development of environmental theories for architects, designers and planners. They determined a way of understanding and classifying the world, through evolution as a survival of the fittest. Patrick Geddes, a Scottish biologist and sociologist, was a pioneer in the evolution of the concept of town planning who drew inspiration of Darwin's evolutionary arguments for their application to cities and societies. To Geddes, this justified human development, and led to a belief that "humans, with their ideals, ethics, perceptions, and activities, supersede their evolutionary nature by virtue of reason, and that this feedback loop pushes societies to evolve further" (Kallipoliti, 2018, p. 14). His works too, by applying theories of evolution to social structures, environments, and the "complex networks of interrelationships between the material constitution of environmental forces, civic life, and built forms" (Kallipoliti, 2018, p. 12) were influential in expanding thinking in design beyond individual products, broadening ecological design thinking of the twentieth century.

Darwin's theory of evolution also aided an understanding of ecology as a set of mechanical rules. Similarly, Biologist Raoul Francé introduced designers, through in his book *Plants as Inventors*, to the idea that plants could offer solutions to technical problems. Prominent figures of the Bauhaus Movement interpreted this understanding of nature in design, including László Moholy-Nagy, through "adapting natural systems to technical artifacts" (Kallipoliti, 2018, p. 16) with a focus on functionality rather than form. Bauhaus leaders were also engaging in interdisciplinary conversations with biologists in the 1920s and 1930s, bridging a connection between seemingly contradictory fields and adopting a comparable view of ecosystems as systems that could be controlled and managed by humans through machine-thinking. The perpetuated design philosophy followed principles of mastery and mechanism in this regard through the reduction of complexity and emphasis on functionality. Unlike the stylistic interpretation of nature in the preceding Arts and Crafts and Art Nouveau movements, designers in the 1920s and 1930s expressed the functionality of nature through their projects. This type of thinking, influenced by Raoul Francé's analysis of plant forms to find solutions to human problems, has been noted as one of the first formal investigations into biomimetic design (Kallipoliti, 2018, p. 17).

Ultimately, design throughout the early twentieth century drew on nature as a model or tool for design, however, under the ideals of integration of humanity, ecology and design, the underlying aim here was still to improve human evolutionary fitness in the sense of Darwin’s theory of evolution. Through ecological design, the evolution of design approaches progressed through the replication of nature as an aesthetic to nature as a system resulting in the synthetic replication of natural systems being included in design thinking. This theme of synthetic replication was paralleled in the rise of synthetic chemistry, this time with the aim of replacing natural products with cheaper, more regulated synthetic chemical products. This type of thinking, as Kallipoliti argues, “signaled the end of nature as an autonomous field and the rise of ecological design as a replication of self-organising cyclical systems instrumentalised through technological mediation” (Kallipoliti, 2018, p. 18), a sentiment carried through into the latter half of the century.

The environmentalist movement *(World War II – 2000s)*

The second half of the twentieth century saw growing concern for the condition of the planet, and the first signs of an awareness of the impact of human activity on the environment. This elevated social awareness, and the emerging environmental movement was landmarked by Rachel Carson’s influential book *Silent Spring*, published in 1962. In her book, Carson drew light on the visible and lasting impacts of human actions of the planet and thereby challenged the idea that humans have the agency to impose technological and chemical control over the planet. Silent spring evidenced this human impact through noticing the implications of the chemical developments in synthetic pesticides, specifically dichloro-diphenyl-trichloroethane (DDT) which is a persistent organic compound that Carson connected with the disappearance of birds, hence a ‘silent spring’. This raised public awareness of the lasting impacts of human intervention on the natural environment and suggested that questions needed to be raised about the human meddling and design of nature, and that out actions can have lasting implications of the environment. By showcasing how our own actions are impacting us as humans through the natural environment helped the movement gain traction, as now, with the view that we are independent from the environment, are in danger of its degradation.

The following period saw growing support for this environmental movement, as humans became aware of worldwide pollution levels and evidently the physical downfalls and excessive waste streams of economic growth. Kallipoliti defines environmentalism, as it emerged in the 1960s and 1970s, as “a broad scientific/ social movement and ideology that advocates the protection and improvement of the health of the environment. Issues of interest to environmentalists include, but are not limited to, climate change, overpopulation, and genetic engineering” (Kallipoliti, 2018, p. 45). This social activism manifested with a focus on the redistribution of global resources, where resources were examined as “interconnected systems that could be redistributed” (Kallipoliti, 2018, p. 3) by human intervention through mechanism and technological thinking. Through this machine thinking, humans perceived technology as a way to control, prevent and correct environmental disturbances, and nature as a source of systems to serve as inspiration or case study to be mimicked for human benefit.

This approach to ecological design represented a paradigm shift influenced by the ecologist’s appropriation of the scientific language and classification tools of cybernetics by diagramming the flow of energy in the natural world as input and outputs, or “circuits in a cybernetic ecosystem” (Kallipoliti, 2018, p. 19). This computational theory of reading the world as a “system composed of subsystems” coincided with views of von Bertalanffy’s *General Systems Theory* of the 1950s, proposing the universe as a “system of systems” (Kallipoliti, 2018, p. 21). Around a similar time, Howard Odum, an influential figure along with his brother Eugene in popularising this approach, invented an energy systems language

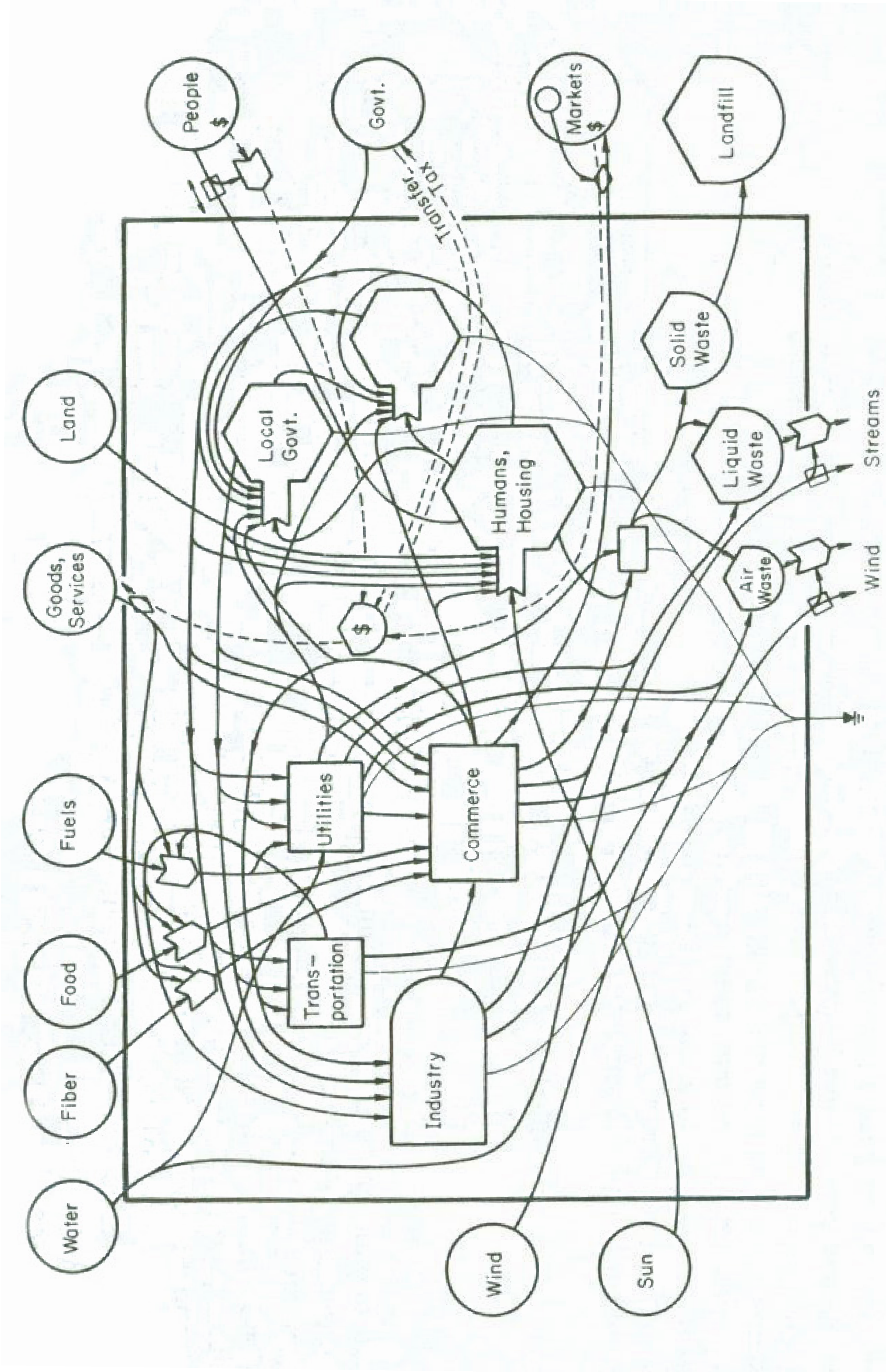


FIGURE 25-21. Representative city system.

05.

Figure 05. *Representative city system:* an Odum diagram of a city

4 See figure 05: *Representative city system Odum Diagram* Page 28

to represent both ecosystems and human agency in terms of input and output flows (Kallipoliti, 2018, p. 19). This representational language became the primary tool for visualising performance and energy flows**4**, particularly in architecture, and shaped approaches to mitigate environmental degradation. Further developing on Haeckel's definition of ecology, which identified the integral link between a living organism and its environment, the Odum brothers understood the science of ecology now to be expressed through the study of ecosystems. They advocated for this science of ecology was to him the key to understanding and managing Earth's systems for the good of humanity and all its life forms. It is in this managing, that we see evidence of the reminiscent human-centric, God-like complex where we believe again that we have the power to control and manage nature, now through ecosystems and technical systems.

This global attitude to environmentalism was similarly characterised by a substantial shift in the 1960s in the nature of the design process, involving now the design of the planet itself, as noted by sociologist and futurist John McHale. In his 1969 book *The Future of the Future*, McHale wrote that "man has enlarged his ecological niche to include the whole planet" (McHale, 1969). This "ecological niche" includes both an attempt at preservation of the planet holistically, but also a dramatic upscaling in what we believe we have the power, and the right, to control and manipulate to our own benefit, with humans at the center of the discussion of both cause and effect.

The momentum in the environmentalist movement led to formalised debates on the limits of economic growth and environmental protection strategies. In 1972, The Club of Rome showcased the first scientific demonstration that we cannot go on exploiting resources at the current rate. With a trust in science established and proven in preceding centuries, this now became a topic to be taken seriously. In the same year, at the Earth Summit in Stokholm, the impact of technology and the necessity to protect the environment was discussed for the first time at a global conference. In 1987, the Intergovernmental Panel on Climate Change (IPCC) was created to provide the world with a clear scientific view on climate change, and the Montreal Protocol scientifically identified and banned gases depleting the stratospheric ozone layer. This, along with the later definition of greenhouse gases at the Earth Summit in Rio in 1992, gave environmentalists at the time a specific, scientific objective in tackling the big objectives of climate change.

In the same year as the IPCC was created, 1987, the Brundtland report of the World Commission on Environment and Development: *Our Common Future* gave the first definition of sustainability by defining that “sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). While the term sustainability is so often associated with environmental protection, the definition proposed by the Brundtland Commission speaks to the needs of humans above other species (St. Pierre , 2019, p. 98). There is still an emphasis on meeting human needs first, as well as an allowance and encouragement of continued development in line with a capitalist growth trajectory. The development of institutionalised policies and criteria following this have therefore most commonly served mainstream corporate values and have therefore been critiqued in various publications for “empowering capitalist production” and creating new economic exploitations “veiled by the ethics of environmentalism” (Kallipoliti, 2018, p. 3).

Still, bringing sustainability and environmentalism into national discussion and policy impacted design and business thinking to follow. It is still under speculation as to whether environmental regulations and policies have actually impacted factors such as carbon dioxide emissions and pollution, however it is clear that these ideas are increasingly more prevalent in design, industry and business discussions.

This period also saw the seeds of a critical reflection of ecological thinking fostered a new perception of our relationship with nature. In 1973, Norwegian philosopher Arne Næss coined the term deep ecology in his article “The Shallow and the Deep, Long-Range Ecology Movement: A Summary”. Critically reflecting on ecological thought, he proposed the concept of deep ecology as a remedy to what he considered a shallow paradigm. His writings established the basis of the philosophy of post-human and more-than-human theories by highlighting “observing and living with nonhuman nature to understand the interconnectedness of all life forms, including humans” (Kallipoliti, 2018, p. 24) as a way re-situate ourselves from the conception of nature as an ‘other’. This thinking is critical in the evolution of the human-nature relationship, nature shifting from the distinct other, to being “with”, “interconnected” and “decentralised” from the human. This thinking gave rise to the post-humanist theories in the 1980s and served as theoretical framework for the more recent design principles and projects.

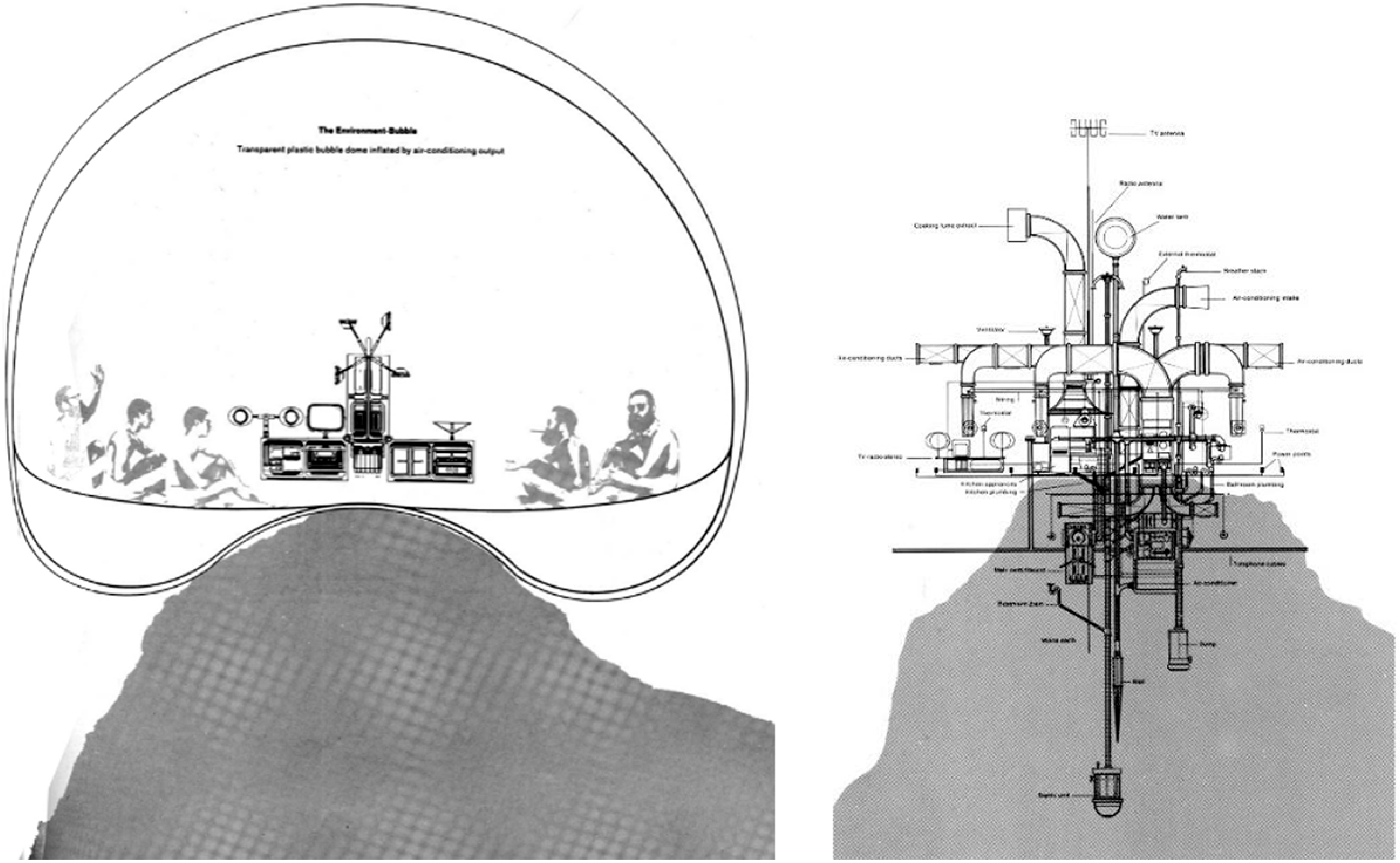
With growing unease in an atmosphere of environmental degradation and the emerging environmentalist movement in the second half of the twentieth century, the response extended beyond policy, movements and writings to a response from the general public. This manifested in many ways, but a general trend towards self-sufficiency and closed-systems thinking, inspired by cybernetic language, became a general theme for social and design movements in this time.

Bioclimatic, or passive solar design, coined by the brothers Victor and Aladar Olgyay, emerged as a specialisation amongst architects of the early 1950s as a way to use buildings as a tool to create comfortable indoor conditions in varying climatic conditions without mechanised systems. The following decade, however, saw the rise of mechanised climatic regulation, with the development of energy hungry air conditioning and humidifying devices. In 1965, Reyner Banham[5] famously introduced the concept of the

5
See case study: *Environmental Bubble*
Ryner Banham: A Home Is Not a House
Page 32-33

Ryner Banham – A Home Is Not a House: Environmental Bubble

Key words: *Self-sustaining, barrier, hygiene, anatomy, atmosphere*



06.

Banham's 'Environmental Bubble' represents an attitude to architecture that is a closed, self-sustaining system, with a strong barrier between the inside and outside world concerned with screening out pollutants and regulating a hygienic interior climate.

In this conceptualisation, a home is represented through the '*Anatomy' of a Dwelling*, drawing parallels with the ongoing emphasis on hygiene within health practices governing practices including architecture and design.

Figure 06. *Un-house* and *Anatomy of a Dwelling:* François Dallegret's illustrations of Bahnam's 'Environmental Bubble' concept published in the 1965 article"A Home Is Not a House".

"Environmental bubble", sealed and atmospherically controlled by mechanical devices (Kallipoliti, 2018, p. 34) in contrast to a passive house of the time which was entirely open and integrating the flows of the outside world.

Similar to the physiological approach to bacteria and the human body, creating a barrier and protecting the inside from outside environmental factors, this Environmental Bubble thinking removes the factor of an uncontrolled environment and isolates the system. These two fields were not so separate at the time, as pointed out by Kallipoliti on Banham's approach, "According to Banham, the word atmosphere was to be read literally; he claims that historically, atmosphere has not only been calculated, but also governed design decisions—decisions undertaken with the aid of medical practitioners" (Kallipoliti, 2018, p. 29) and thereby effectively coupling biology and architecture, he "linked technological developments in regulating the conditions of interior human habitation to a new desire to exert mechanical control over systems in feedback loops" (Kallipoliti, 2018, p. 29). As becoming evident later into the twentieth century, the implications of the human tendency to keep dirt and germs out has ultimately resulted in altering the natural ecosystems we are trying so hard to keep separate, by further polluting and stripping the planet of resources through high intensity machinery in the case of these buildings, and changing the biology of microbes as they respond to human antibiotic endeavors in the case of physiology.

This idea of self-sufficiency categorised many other responses in the latter half of the twentieth century. Younger generations in the United States, in response to the concern for rising levels of pollution and turbulent atmospheres in the 1960s, turned to the survival mechanism known as "dropping out". Literally interpreting Timothy Leary's advice to "Turn on, tune in, and drop out", large groups of people abandoned urban life to establish self-sustained communities. In these communities, the most notable being Drop City in Colorado in 1965, residents were to "recycle their waste, produce and distribute energy, and achieve a degree of autonomy in a restored equilibrium with nature" (Kallipoliti, 2018, p. 22). This emergence of "do-it-yourself" culture was cultivated by Stewart Brand's Whole Earth Catalogue[6], described by Brand himself as an "evaluation and access device". In a bid to empower the individual "to conduct his own education, find his own inspiration, shape his own environment, and share his adventure to whoever is interested" (Brand, 1968, p. 1), Brand opens his first issue in 1968 with the sentence "We are gods and we might as well get used to it" (Brand, 1968, p. 1). This highlights not only the human-centric, God-like complex not unfamiliar to this and preceding times, but also the role of the manual itself in ecological activism and spreading certain visions. Brand's catalogue also instigated the production of further manuals and "do-it-yourself" guides. Although claiming to empower the individual, this unified guide resulted in a distinct and common building language developed through mathematical equations and cybernetic theories.

The concepts of self-sufficiency and autonomous living also became popularised in technologies of the British avant-garde scene of the 1970s. Based on its biological definition, autonomy refers to a "system's organic independence and self- governance" (Kallipoliti, 2018, p. 26), a notion that was adopted by architects and designers to represent the idea of the house or community as a "self-reliant ecosystem, detached from its context … where architecture, systems theory, and human biology could blend together in the hope of a radical social reform" (Kallipoliti, 2018, p. 26). In this way, this conception of autonomy was not only an ecological statement, but a political statement of self-empowerment. With the boom of "urban retreat" through Britain and the United States, experimentation with alternative energy and food production was explored from the early to mid-1970s to support autonomous living[7], as a "political statement against consumerism and capitalism" (Kallipoliti, 2018, p. 28).

6
See figure 07:
Whole Earth Catalogue
Page 36

7
See case study: *Ouroboros Project*
Dennis Holloway
Page 38-39

WHOLE EARTH CATALOG

access to tools

Fall 1968
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WHOLE EARTH CATALOG 1968

PURPOSE

We are as gods and might as well get used to it. So far, remotely done power and glory—as via government, big business, formal education, church—has succeeded to the point where gross obscure actual gains. In response to this dilemma and to these gains a realm of intimate, personal power is developing—power of the individual to conduct his own education, find his own inspiration, shape his own environment, and share his adventure with whoever is interested. Tools that aid this process are sought and promoted by the WHOLE EARTH CATALOG.

FUNCTION

The WHOLE EARTH CATALOG functions as an evaluation and access device. With it, the user should know better what is worth getting and where and how to do the getting.

An item is listed in the CATALOG if it is deemed:
1) Useful as a tool,
2) Relevant to independent education,
3) High quality or low cost,
4) Not already common knowledge,
5) Easily available by mail.

This information is continually revised according to the experience and suggestions of CATALOG users and staff.

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07.

Figure 07. Pages extracted from Brand's *Whole Earth Catalogue,* 1968

With growing awareness for environmental degradation due to waste and pollution, designers began to view buildings as tools to address disturbances, which soon became the focus of architects and designers, replacing functionalism with environmental performance. The Garbage Housing movement, of the 1970s, headed by Martin Pawley, drew literally from the metabolism of nature suggesting an immediate use of wasted materials in a system where consumer by-products were utilised as building materials. Pawley's ideas claimed to address both the problems of excessive waste flows and housing. However, it was the problem of fulfilling technical building standards that overwhelmed the movement, a problem that is still facing new material development today. However, the real drawback of this movement was its single-minded approach to tackling a far more complex problem. With the sincere focus on specific waste, other aspects of material production were forgotten in the environmental debate.

Such processes designed to resemble the metabolism of ecosystems, followed a now cemented approach to using nature as a tool for design through its systems. This concept, echoing the practices seeded during the Bauhaus and the Biotechnik interpretation of natural processes characteristic of the early twentieth century, became formally explained and popularised in 1997 by Janine Benyus' through the book *Biomimicry: Innovation Inspired by Nature* as a design methodology and set of principles. Biomimicry is explained by Benyus as the "conscious emulation of nature" as a means of producing things in an environmentally sustainable way. Its premise is that nature has already developed, with great style and efficiency, solutions to many problems faced by engineers and designers now. Benyus' articulation of biomimicry is contextualised within a greater body of work bringing attention to the complex and toxic relations of capitalism and the environment, including that of deep ecology and ecofeminism asserting the problematic interconnection of radical scientific rationalism and the shift required in humanities relationship with nature. Zimmermann, in line with the deep ecology movement,

Dennis Holloway – Ouroboros Project

Key words: *Self-sufficiency, autonomy, closed systems, energy conservation, waste recycling*

08.

In 1970, as part of Project Ouroboros, named after a mythical serpent which could regenerate by eating its own tail, Dennis Holloway held a competition amongst his students at the University of Minnesota to design a self-sufficient house. The outcome, Ouroboros South, was completed in 1973 and positions itself as an “evolving laboratory for energy conservation and self-sufficiency” (Closed Worlds, n.d.).

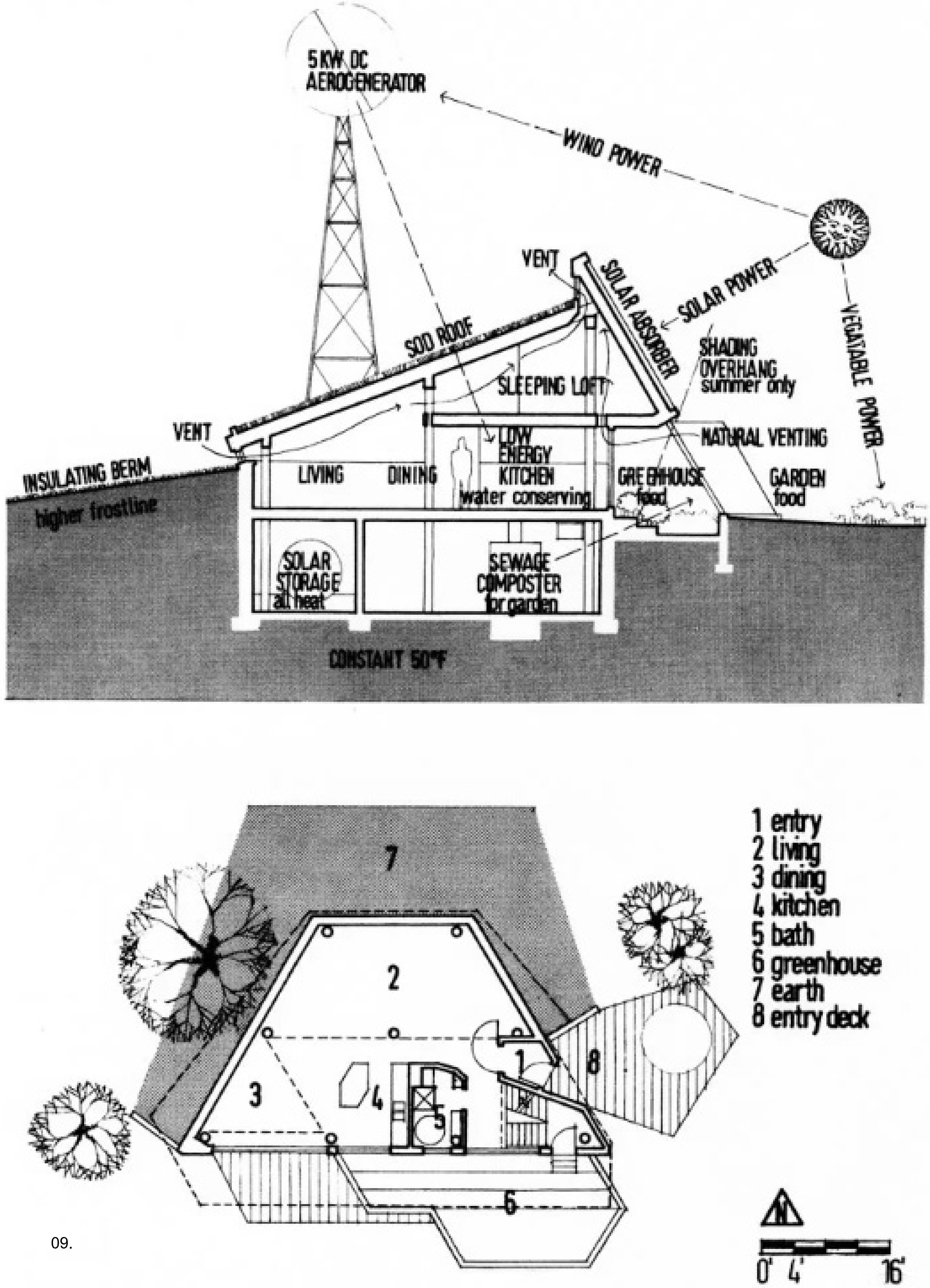
The key self-sufficiency mechanisms tested in this project were solar for heat collection, electricity generation by wind and a sewage system designed for waste recycling with a composting toilet.

This trend of self-sufficiency and autonomy, while developing technologies for off-grid living such as re-use and recycling and energy conservation systems, also supported the idea of the ‘environmental bubble’ by disconnecting the building from its external ecosystem.

Figure 08. *Project Ouroboros South:* exterior photograph of Ouroboros South, Minnesota

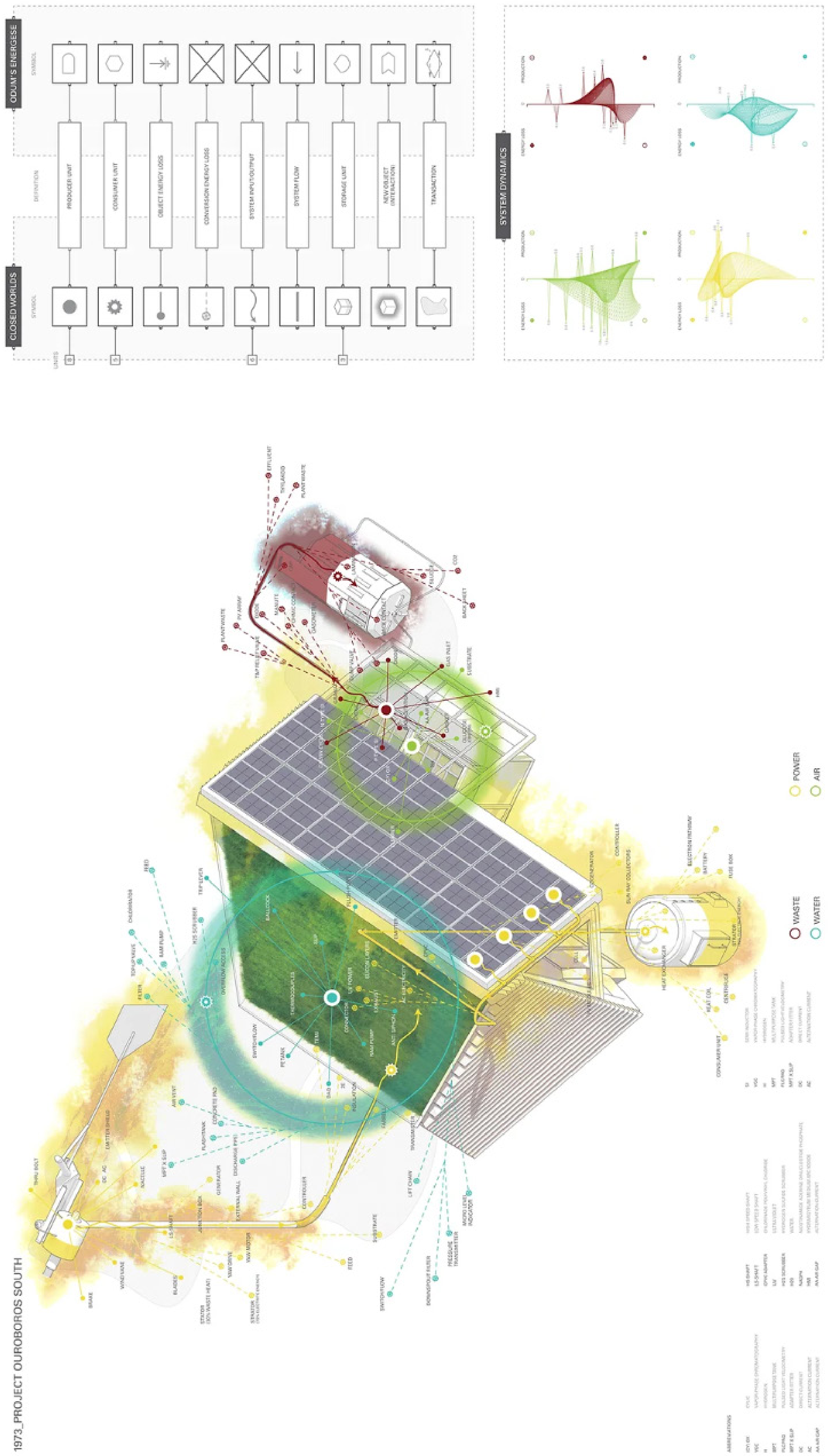
Figure 09. *Project Ouroboros north-south cross-section and floor plan as developed:* showcasing energy, heat and waste systems

09.



had already highlighted that “only a basic shift in humanity’s self-understanding and its attitude toward nature will prevent social and ecological catastrophe” (Zimmerman, 1997, p. 185), however, biomimicry, as defined by Benyus, differentiated itself from existing literature by not just reflecting on this, but actually offering an alternative narrative of our relationship nature. Going beyond just optimising technologies, biomimicry, by positioning us as “natures apprentice”, proposed that we can use nature to help nature, not just as a body of knowledge but also as a system of ethics (Fisch, 2017, p. 1)

From the late 20th century into the 2000s, the philosophy of post-humanism began to challenge the traditional anthropocentric view that places humans at the center of moral consideration. Building upon Næss’s philosophy of deep ecology, thinkers like Donna Haraway, in her work beginning with *A Cyborg Manifesto* published in 1985, and and Rosi Braidotti, with her book *The Posthuman*, explored the entanglements between humans, animals, and machines, advocating for a more inclusive understanding of agency beyond the now blurred boundary between human and its others. With developments in digital technology, our perception of human and other is being forced to extend beyond only natural entities, to imagine a future where we co-habit with digital technology too.



10.

Figure 10. *Feedback loops of project Ouroboros South*: produced by Lydia Kallipoliti and Tope Olujobi for the exhibition “Closed Worlds” in 2016

With growing urgency against complete environmental collapse and more recent epistemological shifts in our understanding of how the world is structured, we are being driven to more critically reflect on how we live with each other and other nonhuman species within a context of ambiguity and complexity.

Benyus has continued, well into the 21st century, to promote and develop her concept of biomimicry as a conceptual methodology and set of principles for discovering and mimicking organic design. In response to a growing understanding of interconnectedness and complexity of the natural world and desire to work with nature, biomimicry in this sense had gained great traction.

However, Benyus' understanding of biomimicry has also come into criticism by numerous authors for objectifying nature and buying into the capitalist agenda. Referencing this work, Michael Fisch argues, in his 2017 paper "The Nature of Biomimicry: Toward a Novel Technological Culture", that while he is hopeful of the message that biomimicry promotes, it "misses the essence of its own radical innovation when in promotes itself as a science of nature" (Fisch, 2017, p. 4), and that it "speaks the language of capitalism and political ecology simultaneously" (Fisch, 2017, p. 10). He attributes these contradictions to a "lack of critical reflection on its methods and categories (which) make it complicit on many levels with the very structure of dominance (social and natural) that it claims to overcome" (Fisch, 2017, p. 10). Later authors such as William Myers (2018) and Louise St. Pierre (2019) have also drawn attention to biomimicry's alignment with economy and industry highlighting the reality that even with positive ecological intentions, nature is still treated as an 'other' to be used now for ideas as well as materials to solve human problems. Myers opposes this conception of biomimicry, saying that we need to go "beyond biomimicry" with what he calls "bio design" which refers to a new design approach which is characterised by the "incorporation of living organisms or ecosystems as essential components, enhancing the function of the finished work". Myers goes on to explain that this approach goes beyond mimicry to integration, seen as a way of "dissolving boundaries between the natural and built environments and synthesising new hybrid typologies" (Myers, 2018). Similarly, he recognises biological processes as a more renewable and less energy intensive alternative to industrial and mechanical systems. His book *Bio Design: nature, science, creativity* showcases a collection of projects that he deems in line with this ethos of production, including examples of self-healing concrete and mycelium composite materials.

Fisch goes further in his critique, emphasising that it is the nature of its own system of "taxonomy" and the act of mimicry in biomimicry that exposes its flaws. Mimicry implies the copying of an original, and therefore "easily becomes entangled in a binary structure of power" (Fisch, 2017, p. 23), and it is in this framework that biomimicry asserts the role of "natures interpreter" alluding a sense of ownership reminiscent of colonial histories. In his own words Fisch explains:

> "Mimicry in biomimicry … rehearses a representational idiom of knowledge that parallels the project in Western modernity of mapping the natural world with all its constituents curiosities, wonders and (savage) cultural others. Mimicry thus rests on an epistemological conceit inherent not only to the natural sciences that it criticises but also to Western imperial and colonial history. That is, in claiming to make available nature's design secrets for emulation, biomimicry claims an exclusive ability to know and represent the natural world. As much post-colonial theory has argued, representation in this regard is invariably a political act of power and privilege" (Fisch, 2017, p. 11)

Fisch opposes the problematic of mimicry with a turn to biomimicry as "inspiration" rather than mimicry, with reference to Neri Oxman's work, in particular her silk pavilion**[8]**. Biomimicry in this regard, is paralleled with the recognising material things as animate and active participants, and that design, rather than being a product of

8 See case study: *Silk I & Silk II*
Neri Oxman
Page 46-53

human reason, refers to the “complex self-organising system that emerges from human and nonhuman interaction” (Fisch, 2017, p. 13). When Benyus’ version of biomimicry sees the need for a clear distinction between nature and technology, where nature is seen as a perfect separate entity to draw reference to, Neri Oxman’s work advocates for a rejection of boundaries, and rather an engagement in dialogue and interactions with material “toward a new arrangement of becoming” (Fisch, 2017, p. 24).

Similarly, the expanding investigation into entanglements between human and non-human species, and the emphasis in recognition of more-than-human agency as inspired by deep ecology and post-humanism took foothold in the field of architecture and design within the 21st century. Designers began exploring ways in which we can design for and with non-humans such as insects[9], animals and microorganisms.

9
See case study: *Ferral Surfaces*
Harrison Atelier
Page 54-59

Terreform One’s Cricket Shelter[10] explores a co-habitation prototype, where shelter and food are simultaneously addressed through an architectural intervention. While exploration into co-habitation and the needs of the crickets as an agent is being addressed, this project is still reminiscent of a human-centric approach in the sense that the questions mainly lie in what the cricket can do for the human, while providing it with the minimum requirements for shelter and ‘range’, rather than thinking through a symbiotic lens.

10
See case study: *Cricket Shelter*
Terreform ONE
Page 60-63

EcoLogicStudio explores a similar idea with microalgae, but more effectively addresses ways in which we as humans impact the wellbeing of the microalgae. Among a body of work exploring this relationship, their Urban Algae Canopy[11], through bio-technological processing, notably interfaces technology, architecture and nature. As with Neri Oxman’s work, digital technologies are embraced as tools to interface the connection between human and nature.

11
See case study: *Urban Algae Folly*
ecoLogicStudio
Page 64-67

Experimentation in the field of developing new materials utilising the natural metabolic processes was born within this design and sustainability discourse. Materials such as biocement and mycelium composites push the boundaries of biomimicry and explore processes of co-production and co-habitation. Not only do these materials embody a complex and interconnected history of sustainability and design, but they also lead to further questioning and new avenues of design thinking.

Recent work exhibited at the Architecture Biennale in Venice in 2023 at the Belgian Pavilion[12] explores possible future engagements that materials made by living organisms such as fungi provoke at a poetic and tactile level.

12
See case study: *In Vivo*
Bento & Vinciane Despret
Page 68-75

Beyond a theoretical design framework, materials made by living organisms such as biocement and mycelium composites, cross boundaries of disciplines, being deeply interconnected with disciplines bacteriology[13] and mycology and the changing perception of microorganisms in chemistry and health.

13
See case study: *Bioconcrete*
GXN, BioMason, Silas Inoue
Page 76-83

Neri Oxman – silk I & silk II

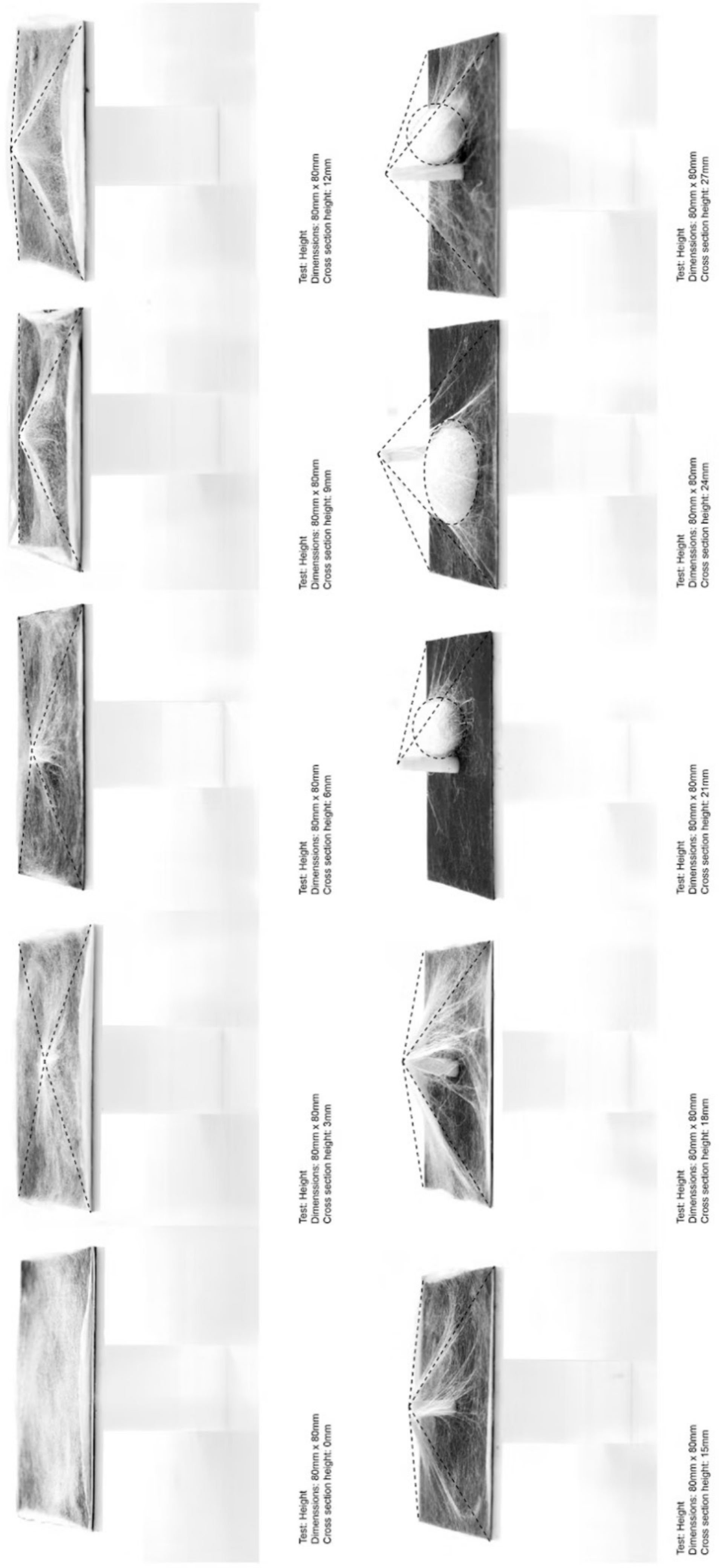
Key words: *co-fabrication, robotics, extraction, shaping biologies, communication, language, environment*

Neri Oxman’s research explores themes of co-fabrication, particularly through the ‘Silk Pavilions’, which are conceived as a collaboration between the fabrication capacities of humans, robotics and silkworms. Oxman’s co-fabrication work responds to the question of how technologies can enable co-design, co-manufacturing and co-habitation across species .

These projects apply design templating techniques as a way to approach the interface with biological organisms. This recognises the agency of non-human organisms in the continuous deformation and alteration of geometry and structure as a paradigm named bio-homeomorphism. By recognising this, Oxman’s work develops strategies for conditioning the behavior of the ‘agent’ to thereby condition silkworms to spin in sheets instead of cocoons opening up possibilities for reshaping co-fabrication practices and the silk production industry (Neri Oxman, n.d.). Her methodology, in this way, shows how we can come to understand non-human agents through technology and adapt our own actions to influence their actions, and maybe ‘biologies’ too.

Figure 11. *Templated response to height:* mapping silkworm responses to environmental conditions

11.



12.

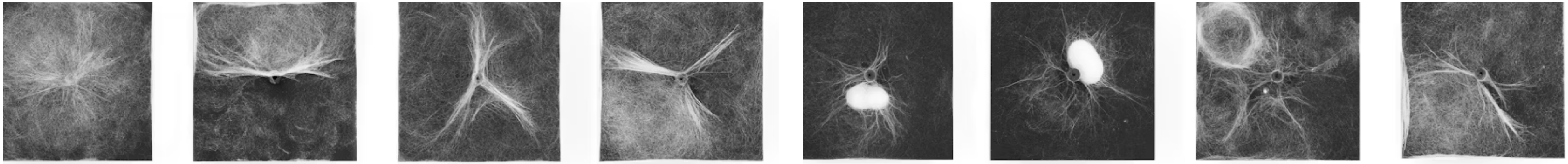
13.

Silk Pavilion I was developed in 2013, inspired by the ability of the silkworm to spin a three-dimensional cocoon out of a single thread. The three-meter-wide dome was constructed in three weeks by 6,500 live silkworms (Neri Oxman, 2013). By studying the spinning behavior of the silkworms in relation to their spatial and environmental conditions through tracking, Oxman and her team were then able to learn ways to guide the silkworm's behaviors to achieve desired forms, working with robotics as a language for more-than-human communications.

Figure 12. *Silk Pavilion I dome:* showcasing biologically spun silk over robotically spun silk

Figure 13. *Silkworms working on spinning the structure*

14.



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The second silkworm-spun pavilion, Silk Pavilion II, was exhibited at MoMA, New York in 2020. This structure, scaled up from the first version, is six meters tall and five meters wide and builds upon prior research to tackle challenges of scale and sericulture, the silkworm industry (Neri Oxman, 2020). In this, Oxman is considering complex topics of interspecies ethics in production processes which were previously disregarded for silk production.

Figure 14. *Silk Pavilion II at MoMa:* exhinition of Oxman's second Silk Pavilion in New York

Figure 15. *Height as template for silk deposition:* learning behaviors

16.

In response to addressing ideas of labour and agency of silkworms, Oxman proposes that in contrast to the traditional silk industry where larvae are boiled in their cocoons in order to extract silk, silkworms in these processes are allowed to live and metamorphose and fulfil the metabolic processes through a full life cycle (Neri Oxman, 2013). This, she considers, is a more ethical and less extractive approach. Oxman's projects propose new ways of silk extraction combined with material production methods which are in tune with the natural processes of non-human organisms in an aim to move away from extractive thinking and enable new structural forms.

Figure 16. *Silkworm with magnet attached:* for monitoring behaviors

Figure 17. *Female silkmoths laying eggs within circular vessels:* thereby living out full metabolic life cycle

Figure 18. *Close up of fertilised silkworm eggs*

Figure 19. *Sheets of silkworm eggs from a single strain*

Figure 20. *Fertilised silkworm eggs preserved in cold storage*

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Harrison Atelier – Feral Surfaces

Key words: *feral, habitat, biodiversity, client, mycelium, hempcrete, modules*

Harrison Atelier’s ‘feral surfaces’ projects encompass an ongoing body of research, literature, design and experimentation that aims to address how a city’s built surfaces can become “textures for life” rather than “screens for display” (Harrison Atelier, 2022), and how non-human life can be considered in design as a client. The design projects showcase how architectural surfaces can create habitats for multiple species to increase the biodiversity of urban ecosystems. Their projects also explore sustainable materiality including mycelium and hempcrete in developing modular habitation units with a primary focus on bee habitats.

Projects include the development of habitat modules that are incorporated into installations, with larger city scale integration proposals including *On the ground: storefront* design, 2023, and *Reusing Rooftops* in Barcelona, Spain, 2024.

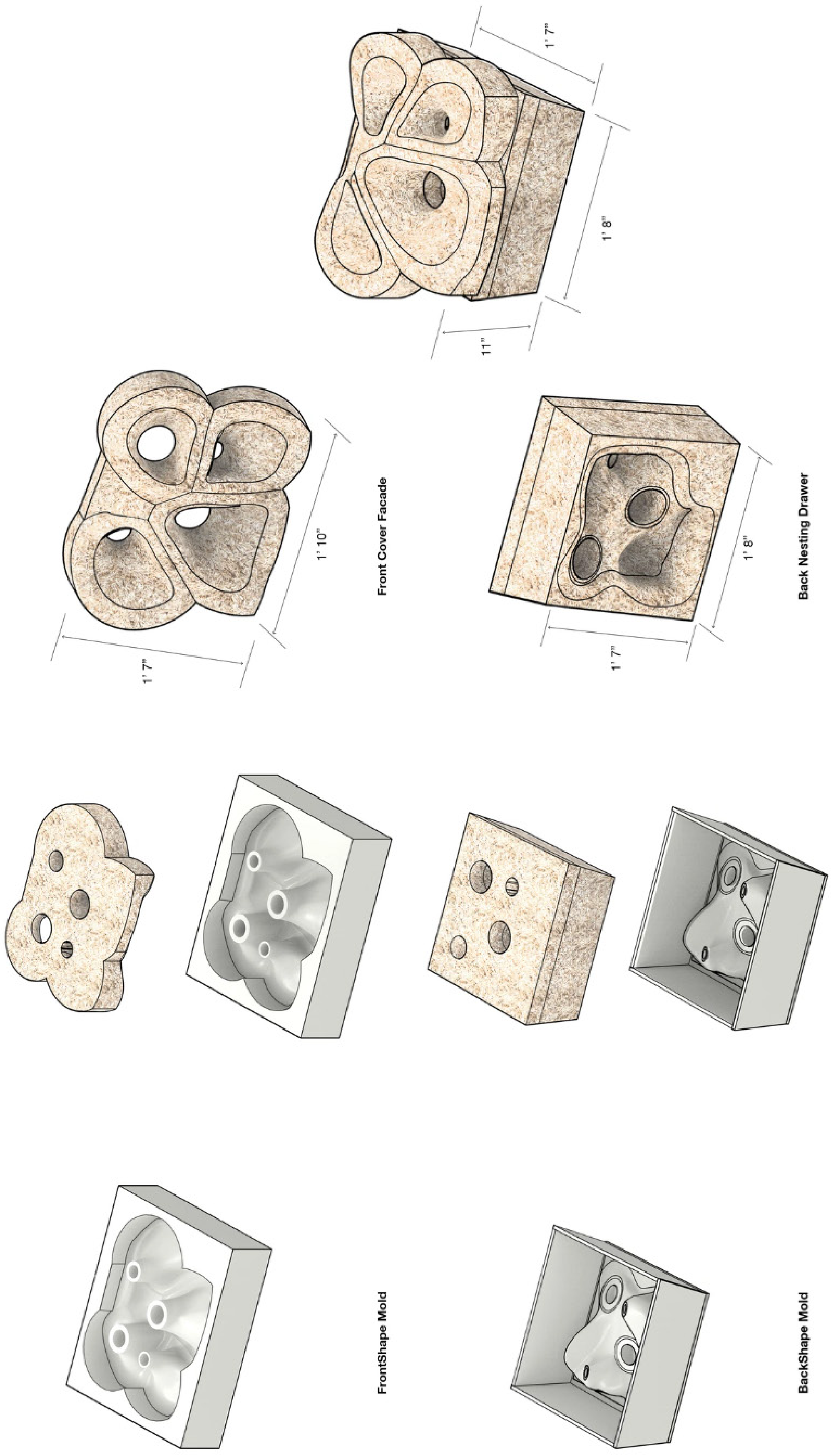

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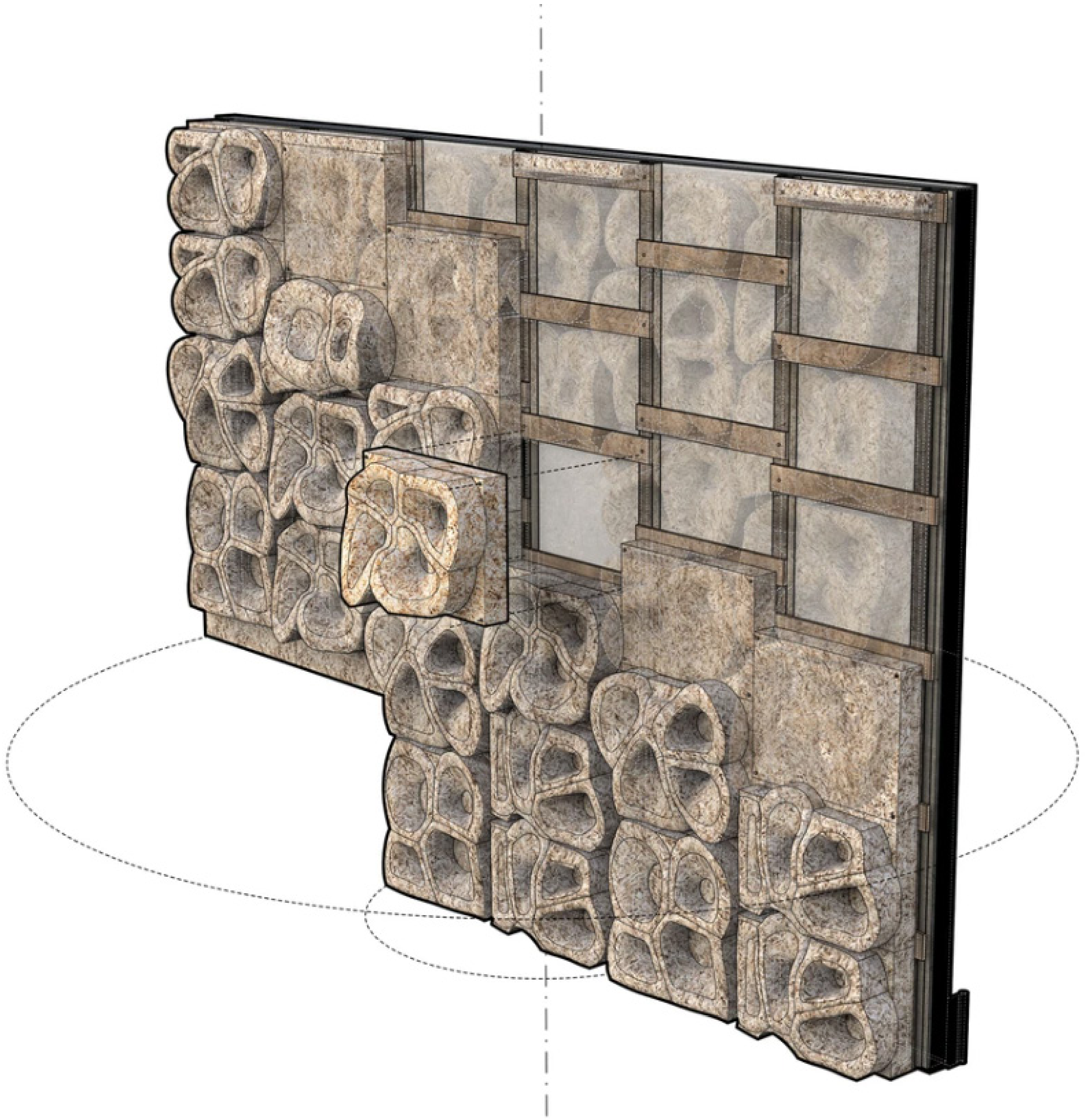
Figure 21. *On the ground: storefront mycelium block modules:* feral surface units design to be a habitat for pollinators in urban environments



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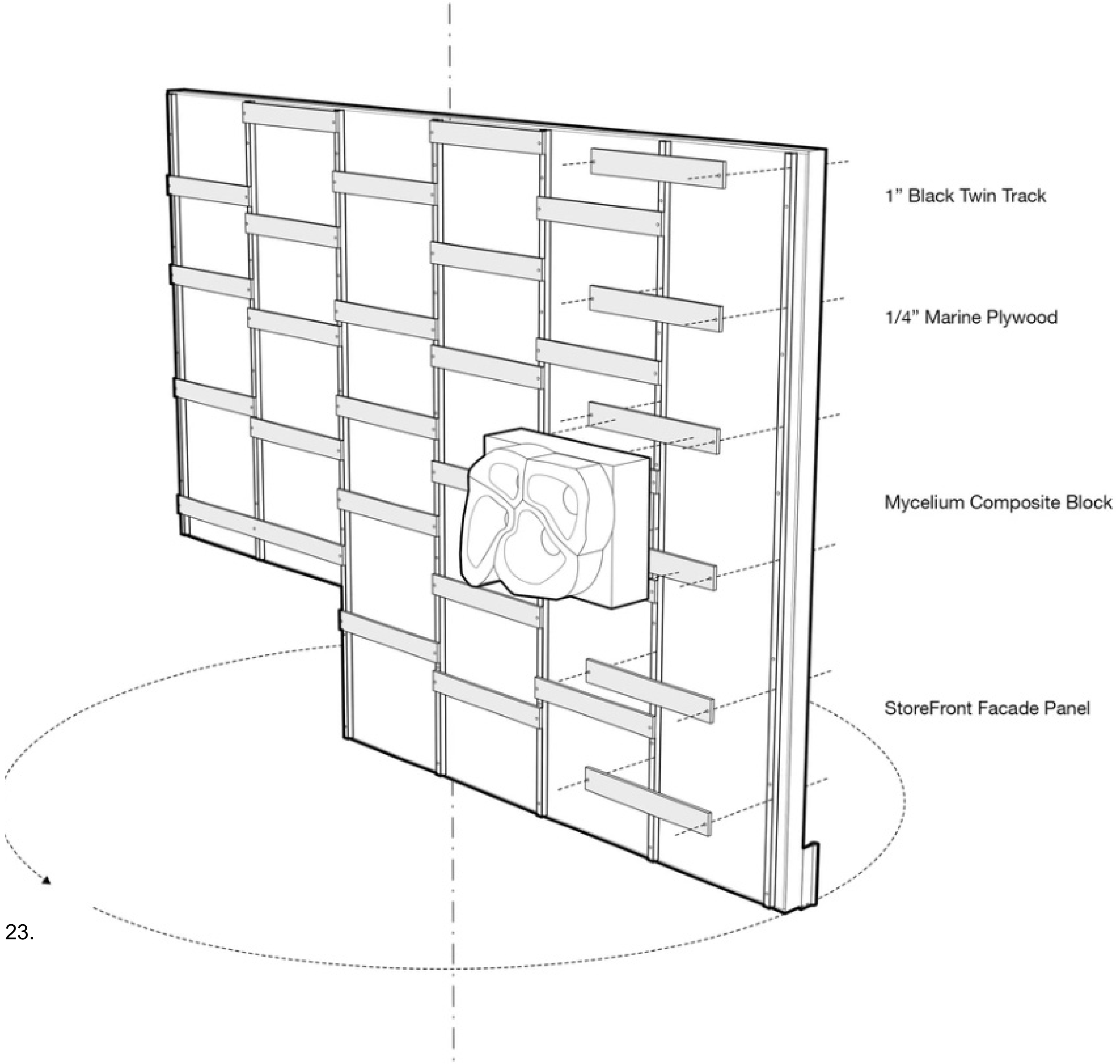

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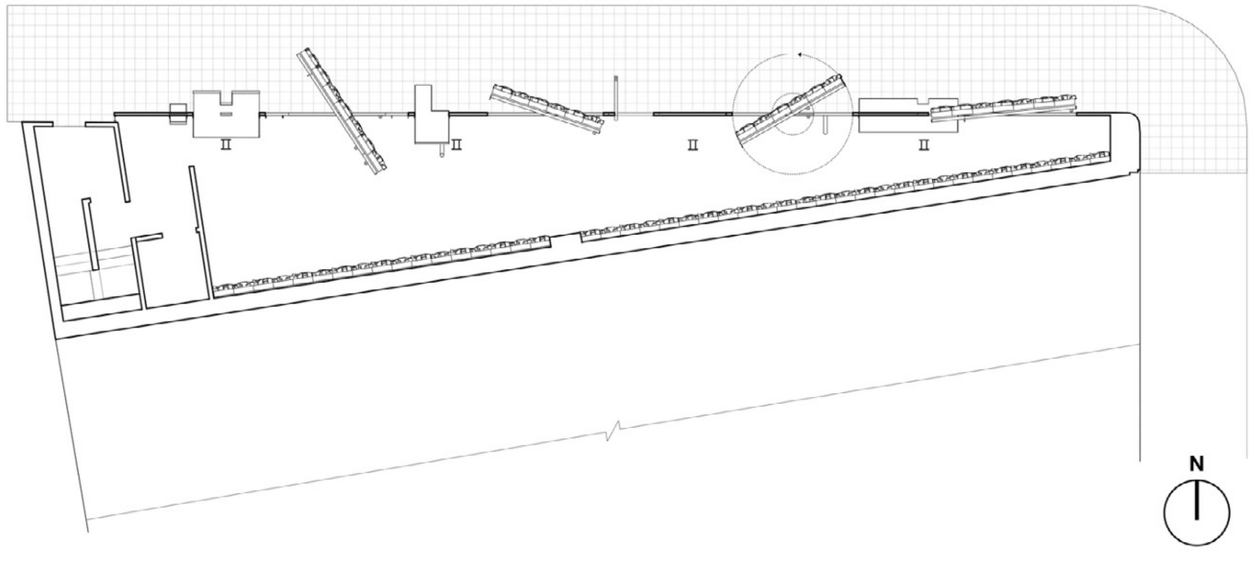
The *On the ground: storefront* design, conceptualised for a storefront in New York addresses both insulation and biodiversity habitats, where Harrison Atelier proposes using a mycelium-hemp module habitats to create habitable screens which serve as insulation too. Thereby, as the studio describes, “the storefront can be re-conceptualised as a non-human space that harbor habitats within the city” (Harrison Atelier, 2023). The proposed storefronts are composed of mycelium blocks which cavity-dwelling native bee habitats, monitoring systems, and plant pockets. In winter the storefronts provide necessary thermal insulation, while in spring the storefront could be detached and redeployed to community gardens. This showcases adaptability with changing environments and non-human behaviors.

Figure 22. *On the ground: storefront facade panel drawing:* panel render showcasing how units are supported arranged on adaptable storefront panels

Figure 23. *On the ground: storefront facade panel components:* diagram explaining components and mechanisms

Figure 24. *On the ground: storefront plan:* showcasing rotating panel habitats for adaptability



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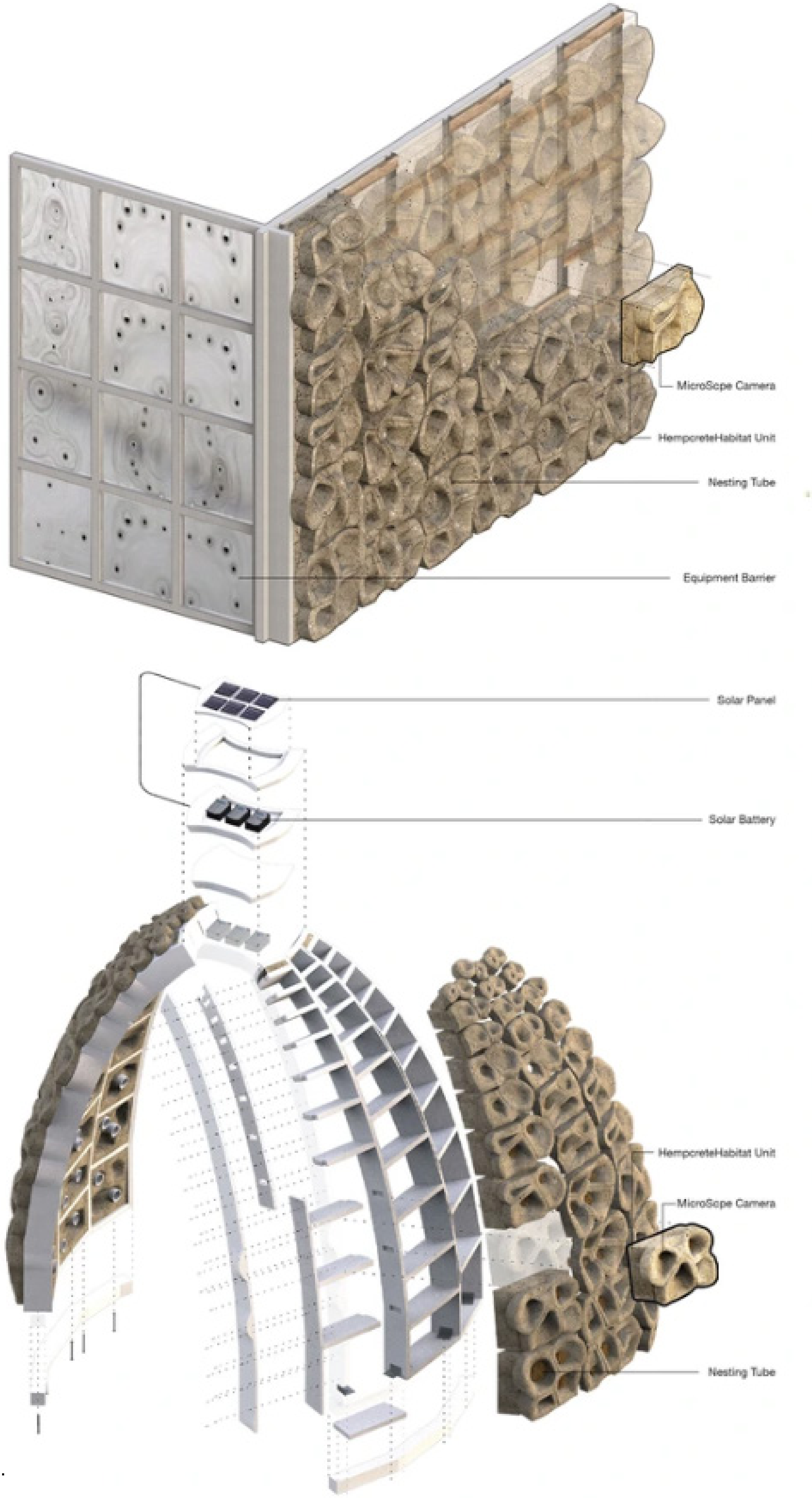
The most recent proposal for Barcelona's Model Architecture Festival scales this concept to a 2500 square meter landscape. Addressing the use of available rooftops in Barcelona, the proposal aims to use these spaces to increase biodiversity in cities and showcase how architecture can contribute to this by designing intelligent analogous habitats. The project also aims to contribute to the existing biodiversity atlas by attracting and identifying by means of cameras embedded in the units, pollinator species in the area. The units, like those proposed for the storefront concept, are articulated in wall facades. Harrison Atelier, through these projects, aims to design for non-human actors as a client, as well as looking at the city as a diverse more-than-human ecosystem.

Figure 25. *Reusing rooftops module visualisation:* feral surface units in place inhabited with insects with vegetation

Figure 26. *Reusing rooftops module:* close up of unit materiality

Figure 27. *Reusing rooftops pollinator habitat system:* pollinator habitat detail, designed for native cavity-dwelling bees

Figure 28. *Reusing rooftops structure exploded detail drawings*: of wall and dome structures supporting pollinator units proposed to be placed on rooftops



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Terreform ONE - Cricket Shelter

Key words: *human and non-human shelter, co-habitation, farming, free range, hygiene*

This project was born in 2016 as a response to the global food distribution problems such as the high greenhouse gas emissions and resource extraction caused by the high consumption of livestock as a protein source. Along with the UN mandate for insect sourced protein, the US based designer Terreform ONE proposed the Cricket Shelter, a modular edible insect farm which proposes an alternative to livestock farming which releases much less greenhouse gas (1%) and requires a much smaller portion of land (0.001%) to produce the same amount of protein as cattle farming (Terreform ONE, 2016).

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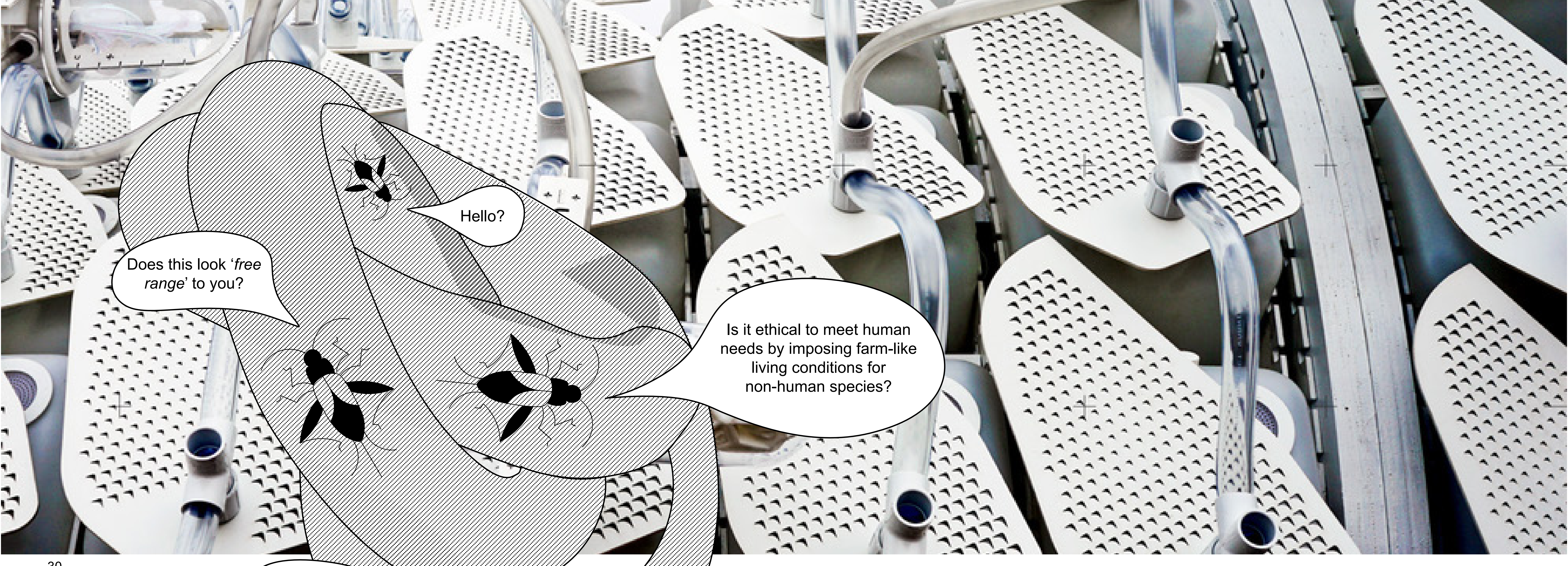
Figure 29. *Cricket Shelter exterior:* prototype Cricket Shelter at Art Basel Miami



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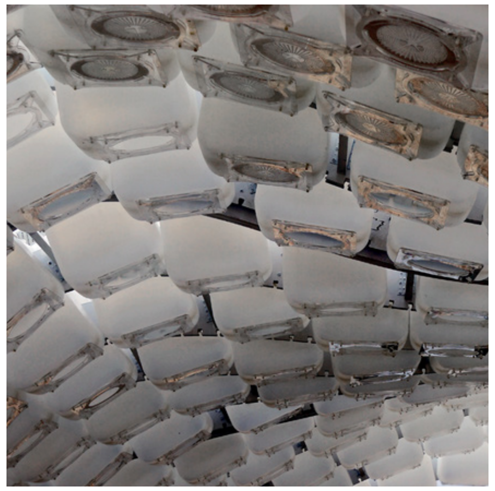

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The project was developed with the aim of prototyping a modular architectural system that could be implemented in “distressed regions” globally with the aim of addressing both food and shelter. The prototype is composed of an interconnected array of structural pods designed to be self-sufficient in supporting the life cycle of crickets. The design claims to adress both ideas of ‘free range’ for the crickets and sanitation and hygiene for humans by proposing an internal ecosystem of modules linked by tubes. While effort has been made to address both the needs of human and non-human life, this conception of ‘free range’ should remain open to further speculation.

Figure 30. *Cricket shelter module external detail:* exterior cladding and tubes connecting modules designed to enable ‘free range’

Figure 31. *Crickets in tube:* commentary on conceptions of ‘free range’ and ethics of farming practices. Drawing by author, 2024

Figure 32. *Cricket in tube*

Figure 33. *Cricket shelter modules internal detail:* crickets inhabiting prototype modules on the interior of the shelter

Figure 34. *Cricket shelter interior:* rows of modules in composed prototype roof

EcoLogicStudio – Urban Algae Folly

Key words: *microalgae, photosynthesis, bio-digital technology, symbiotic relationships, communication*

The London and Turin based ecoLogicStudio exhibited their Urban Algae Folly interactive pavilion at the EXPO Milan 2015 Future Food District. The pavilion integrates living micro-algal cultures into its materiality to showcase the potential of a bio-digital architectural future.

The design of the panels used in the structure allow for both human comfort and stimulate the growth of the microalgae, in this case Spirulina. As Spirulina are photosynthetic organisms, larger volumes of sunlight cause them to grow rapidly, thereby creating more shading potential and increased visitor comfort. In turn, the presence of visitors activates a digital regulation system which stimulates the oxygenation, solar insolation and growth of the algae. In this way, ecoLogicStudio aims to use bio-digital technology as a communication tool to facilitate a symbiotic form of architecture that facilitates interactions between humans, microalgae, climate and digital control systems.

35.

Figure 35. *Urban Algae Canopy:* standing underneath the canopy at EXPO Milan 2015


36.

Microalgae such as Spirulina are nutrient powerhouses, containing minerals and vegetable proteins that are essential to the human body. They also absorb CO_2 even more efficiently than large trees. This project therefore addresses the interface of a range of fields including food security, energy, climate and architecture and showcases how these elements can intersect and interact aided by digital tools.

EcoLogicStudio views traditional planning tools inherited from modernity which are reliant on typological segregation of functions as obstacles to co-evolution. Through their projects they try to recognise biological networks and design manmade systems which are co-evolutionary with these biological networks (ecoLogicStudio, 2017), shifting the narrative of the human-nature relationship.

Figure 36. *Urban Algae Folly close up:* detail of Urban Algae Folly microalgae panels and connections

Figure 37. *Close up of Spirulina encased in panels of Urban Algae Folly*


37.

Bento & Vinciane Despret – In Vivo

Key words: *mycelium, insulation, narrative, tactile, poetic, future speculation, co-habitation, mycelocene*

The Belgian Pavilion at the Venice Biennale showcased Bento and Vinciane Despret's In Vivo project which explores a new relationship between architecture and resources. The exhibition explores mycelium as an alternative building material derived from living organisms and the accompanying imaginary.

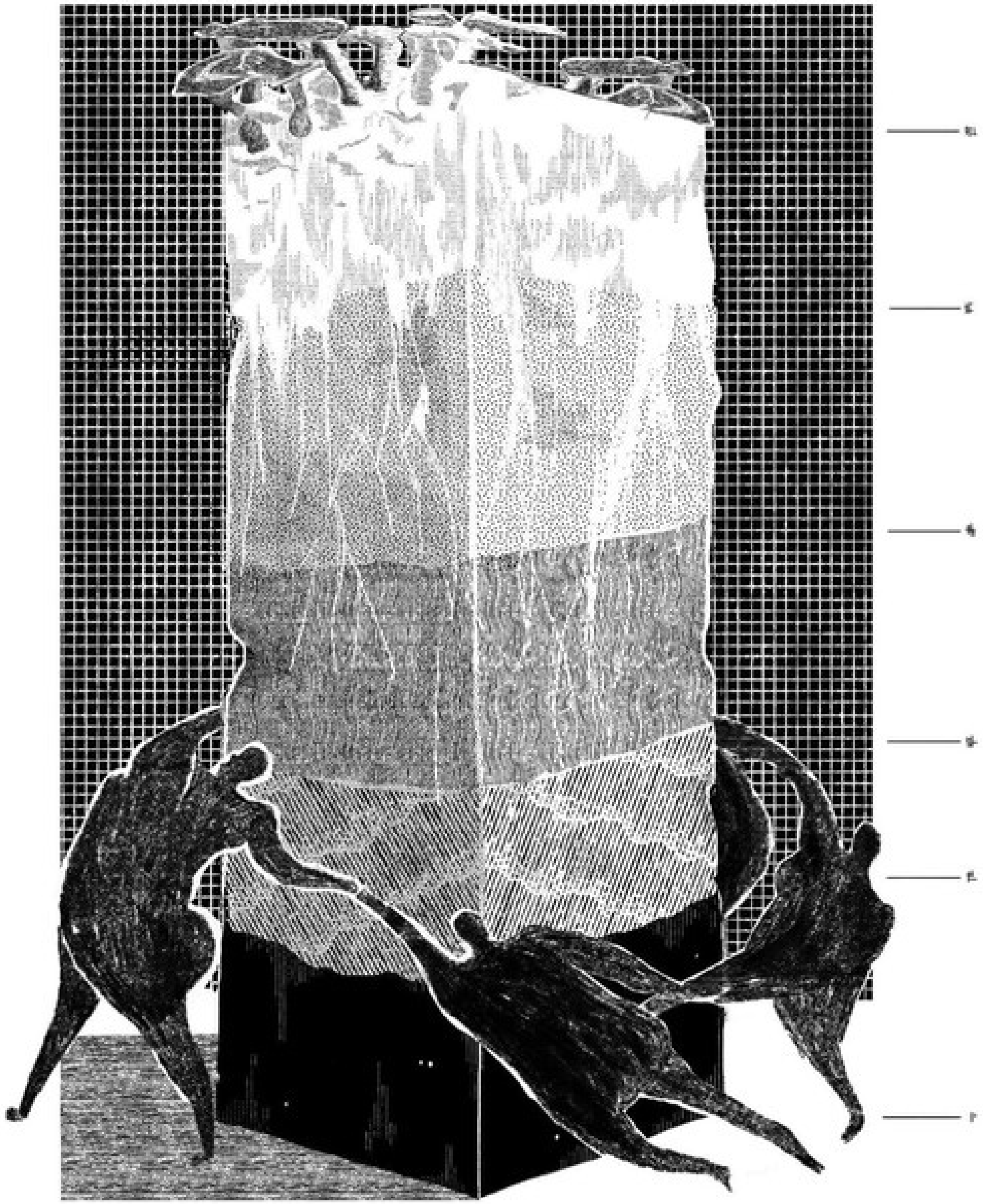

Figure 38. *Fragment No.16-OR17 Mycelium block drawing:* artwork displayed as part of In Vivo exhibition

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The exhibition is centered around a large (12m long x 6m wide x 6m high) installation made of mycelium panels supported by a timber structure which the visitor can enter, touch and connect with firsthand. There is careful consideration to sustainability with materials locally sourced and design for dismantling to be given a second life by Re-Biennale (Belgian Pavilion, 2023). Surrounding the central room, there are installations dedicated to the production and experimentation processes showcasing raw materials, live mycelium and visual iterations of mycelium products. The exhibition is also enhanced with artwork and quotes to support the narrative (see figures 38, 41 and 43) with a strong emphasis on the poetic and tactile nature of mycelium materials.

Figure 39. *In Vivo central structure:* mycelium insulation panels supported on timber structure. Photograph by author, 2024

Figure 40. *Aesthetic variation of mycelium materials:* showcased at the Belgian Pavilion, In Vivo. Photograph by author, 2024

The exhibition is supplemented with a catalogue which is presented as a narrative of the anticipation of the ‘mycelocene’, a new proposed era characterised by the recognition of the agency of non-human organisms and their relationship with humans, following this project. The narrative explores past, present and future accounts from multiple real and imagined voices including letters, extracts from mycological and philosophical texts, an anthropologist’s field notebooks, reports by psychologists, historians and experts in therolinguistics, the study of non-human languages and literature (Belgian Pavilion, 2023), and thereby even the fungi themselves. This narrative investigates the relationship between architecture and fungi, exploring and imagining the possibilities of future collaborations and what it means to co-habit with non-human beings.

The exhibition and accompanying narratives are useful to explore both the practical, aesthetic and tactile qualities of mycelium as a material, combined with the poetic narrative and artistic expressions inspired by interaction with the organism itself, and exploring the complexities of futures this inspires.

Figure 41. *Anecdotes from fungi:* as displayed in the Belgian Pavilion, In Vivo. Photograph by author, 2024

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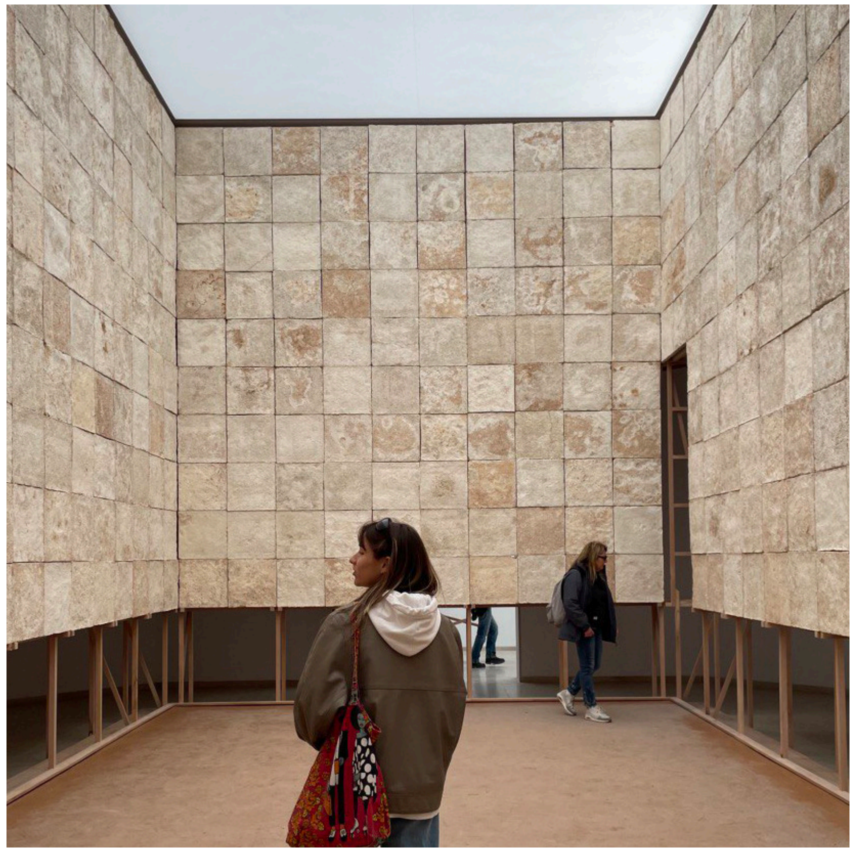

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Figure 42. *Humidity control:* supporting active substrate inoculation at Belgian Pavilion, In Vivo. Photograph by author, 2024

Figure 43. *Artwork of interior of Belgian Pavilion with dancers:* artwork bringing life to central exhibition space

Figure 44. *Central exhibition space being inhabited:* during In Vivo exhibition. Photograph by author, 2024

GXN, BioMason, Silas Inoue - Bioconcrete

Key words: *biocement, technical, environmental, scalability, materials sustainability, aesthetics, narrative, interspecies solidarity*

In a collaboration between the Copenhagen based design-driven research studio GXN, Danish artist Silas Inoue and biocement pioneers and producers BioMason, the 'Bioconcrete' project was developed and exhibited as part of the "Reset Materials: Towards Sustainable Architecture" exhibition at Copenhagen Contemporary in 2023.

The project looks to the future of biocement, testing BioMason's cement for structural applications at the scale of an architectural column. While recognising that concrete is a critical material for social and economic development, the researchers at GXN aim to "expand our definition of what concrete is, to enable material solutions that can still be environmentally conscious" (GXN, 2023). This project aims to address the current barriers for the implementation of biocement, expanding on BioMason's developments from an architectural and artistic perspective, addressing ideas of scalability and aesthetics.

Figure 45. *Bioconcrete column at Reset Materials:* exhibition at Copenhagen Contemporary

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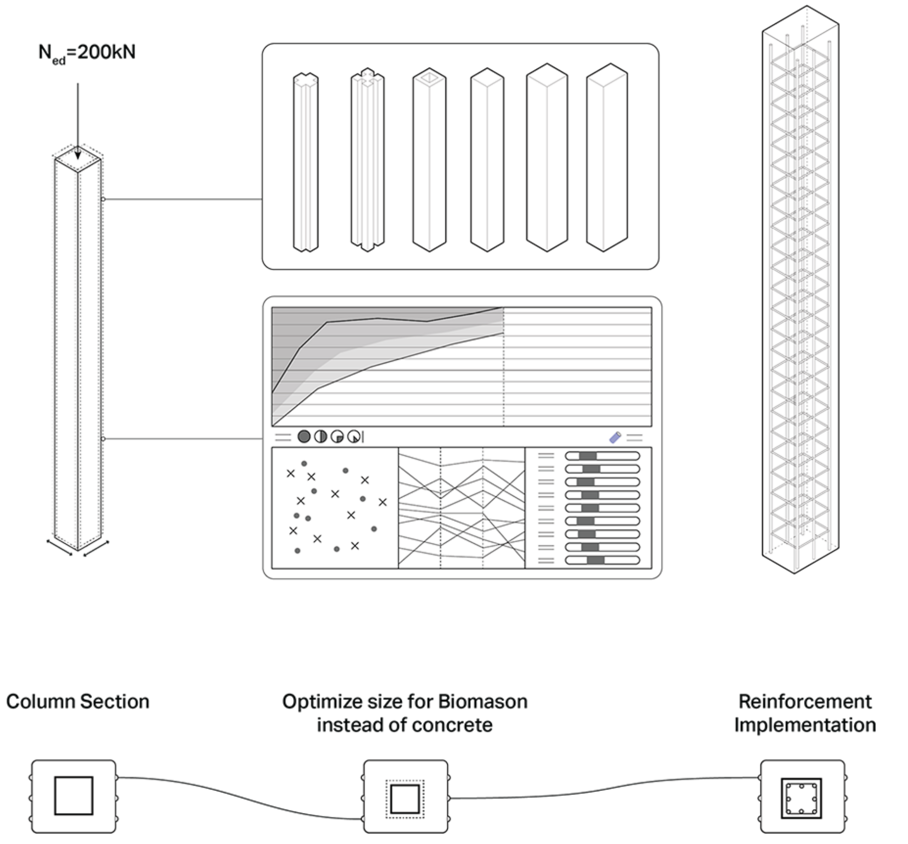
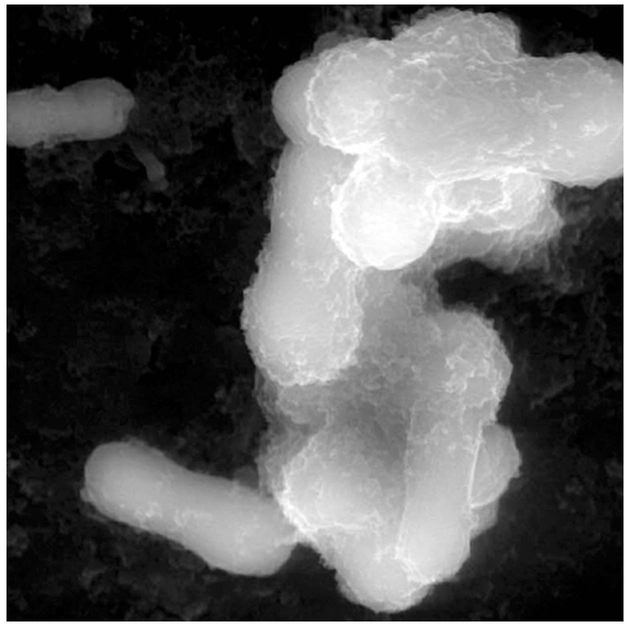


The column was developed for this project as GXN wanted to look to “the most historic and ordinary of architectural elements” (GXN, 2023) to test and showcase the potential for an imaginary where a building system could be fully grown by natural processes with minimum human intervention. The column biocemented in three days, and the final product was identified to be three times stronger, 20% lighter and required only one third of the reinforcement of a regular concrete column (GXN, 2023), while significantly reducing CO_2 emissions, situating the project in light of a promising future for sustainable architectural materials.

Figure 46. *Optimisation of BioMason’s bioconcrete:* optimising form and properties of novel bioconcrete material by BioMason

Figure 47. *Bioconcrete column in formwork:* ‘drying’ in formwork while bacteria are working to bind aggregates

47.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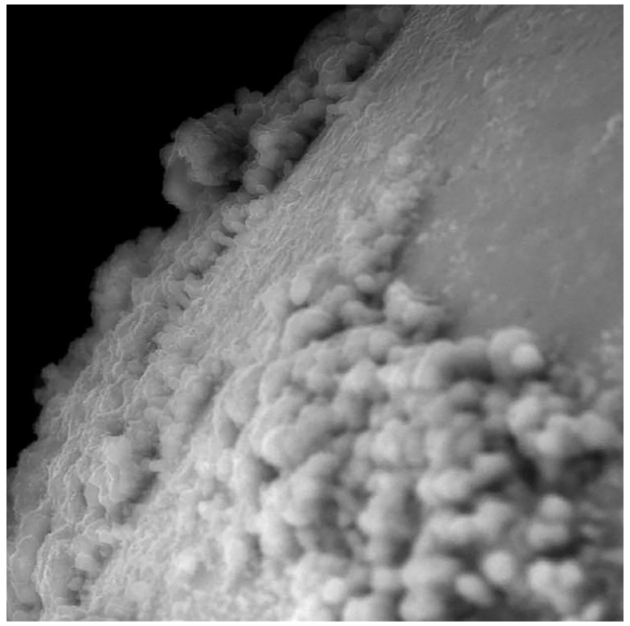
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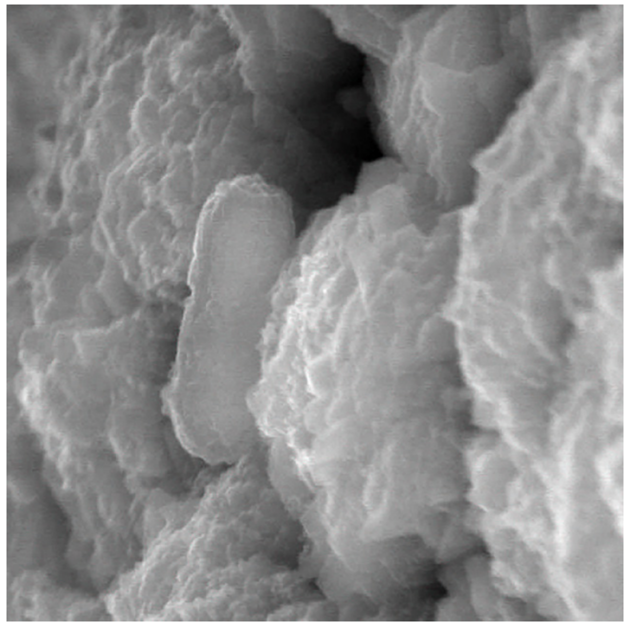
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Figure 48. *Bacteria: Sporosarcina pasteurii:* microscopic image

Figure 49. *Encrusting: Ureolytic biomineralisation:* microscopic image

Figure 50. *Calcium Carbonate ($CaCO_3$) formation:* microscopic image

Figure 51. *Bioconcrete column texture:* close up materiality texture of final column product


51.

52.

The artwork, produced by Danish artist Silas Inoue using BioMason's material, addresses ecological imaginaries concerning architecture and the built environment. The bioconcrete panel depicts a snail shell, also a biomineralisation process, with roots and branches, signifying commonalities between human and non-human life through linking nerves and roots as organic systems. The artwork aims to suggest cross-disciplinary solidarity, inspiration and care as a way of liberating ourselves from both the material and ideological constraints of a fossil-fuel, consumerist economy (GXN, 2023).

Therefore, through an artistic collaboration, both the practicality and scalability of a material can be expressed as well as its accompanying artistic narrative to create a deeper understanding of the roots of the process and address interspecies ethics.

Figure 52. *Reset Materials exhibition pieces render:* axonometric render of components displayed in exhibition including bioconcrete column and artwork produced by Silas Inoue to show scale and elements

Figure 53. *Bioconcrete artwork:* piece by Silas Inoue representing interspecies solidarity

53.

2.2. Historical overview: **Changing attitudes towards microorganisms**

Timeline: *1700s - 2024*

Microorganisms, as we now know, are an integral part of all ecosystems. In understanding forests and even our own bodies, our knowledge and perception of microorganisms has shaped the way we approach health, industry, synthetic production and even inspired us to understand the world and our positioning within it in new, interconnected ways.

Tracking the history of chemistry as a discipline reveals interesting relations in the way that we as humans have positioned ourselves in relations to nature, or the natural. This relationship between synthetic and natural is an evolving relationship, with shifting respect and dominance for nature and natural production. An understanding of this relationship is particularly relevant when we explore ideas of biofabrication as with biocement and mycelium composite materials.

The rise of Chemistry *(scientific revolution-1860s)*

Themes of control and rationalisation are evident through the popularisation of chemistry in the 1700s and 1800s. This can be seen in the medical field where, when being led by chemistry, the approach moved from a concern with treating patients to treating diseases. This is representative of the eroding belief in the mysticism of life, or the ”divine spark” of living matter, rather being replaced by a rational discipline, which became the dominant means of technologically explaining living processes (Bud, 1993).

Admiration for chemistry and its potential was cliché of the nineteenth century, and in so provides interesting commentary on the way that humans viewed nature and ourselves. As representative of the attitude towards chemistry at the time, Mary Shelley accounts of a teacher, Professor Walden, in her novel *Frankenstein*, published in 1818:

> “The ancient teachers of this science (chemistry) promised impossibilities and performed nothing. The modern masters promise very little… But these philosophers, whose hands seem only made to dabble in dirt, and their eyes to pore over the microscope or crucible, have indeed performed miracles. They penetrate into the recesses of nature, and show she works in her hiding places. They ascend to the heavens: they have discovered how the blood circulates, and the nature of the air we breathe. They have acquired new almost unlimited powers; they can command the thunder of the heaven, mimic the earthquake, and even mock the invisible world in its own shadows.” (Shelley, 1818, p.30)

In 1828, Friedrich Wohler showed how urea[14], a natural product, could be made artificially, signifying a radical change in the distinction between natural and chemical products, so far so that Bud identifies that this may be the “moment in which it (the distinction) disappeared” (Bud, 1993, p. 10). The implications of this further reinforced man’s belief in his own self-proclaimed power and control over nature, now possessing the knowledge to become independent of natural resources. This discovery also had great economic potential, affording organic chemists the possibility to replace laborious and expensive extraction of natural products by laboratory synthesis (Bud, 1993, p. 11).

Organic chemistry, the chemical synthesis of natural products, through the distinction of natural and chemical, and the ability to replace natural resources more economically serves an interesting lens to observe the development of the relationship between human and nature, and the human sense of self and other. These discoveries supported a god-like complex in humans, as showcased previously in Shelley’s account of modern chemistry masters “ascending to the heavens” and acquiring “almost unlimited powers” (Bud, 1993, p. 10). Supported by these beliefs, the field of synthetic organic chemistry dominated thinking for the majority of the nineteenth century.

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[14] Note: Urea required as resource for urea hydrolosis MICP processes for biocement production

Zymotechnology *(scientific revolution-1860s)*

Leaning on the popularity of chemistry towards the end of the seventeenth century, the first bid for intellectual authority over the commercial processes of fermentation were recorded by Georg Ernst Stahl in his book *Zymotechnica Fundamentalis*, published in 1697. Stahl expressed for the first time that an understanding of the scientific basis of fermentation could be harnessed to the improvement of commerce (Bud, 1993, p. 9). This introduction of the concept Zymotechnia, or Zymotechnology, can be seen as the first emergence of what transitioned into what we now know as biotechnology, constituting a vital stage in bridging the gap between biotechnology’s ancient heritage in fermentation and its modern associations as a scientific discipline (Bud, 1993, p. 7).

Zymotechnology, deriving from the Greet root ‘zyme’ meaning leaven, originated with the transition in the understanding of the practice of alcohol production. The manufacture of alcohol, previously understood through a combination of cosmic theory and practical skill, was now coming to be integrated and understood through science, a transition in knowledge paralleled with dominant transitions in belief systems across disciplines at the time. Although its roots were in brewing, Zymotechnology became representative of a way to explain all types of industrial fermentation, leaning again on “chemistry’s promise to explain and control” (Bud, 1993, p. 8).

In a bid for the claim of control of the fermentation process, the chemist Justus Liebig who explored a radical reduction of physiological processes to the transformation of chemicals, thought to explain the fermentation process as being a result of the transmission of atoms between yeast (unstable bodies) and sugars (victims). A pivotal point in this understanding, and a catalyst for a new exploration and understanding of human-nature relationships that is continually explored, would follow in 1857, with Pasteur’s demonstration of fermentation as the result of the action of live microbes. With this, he constructed the entirely new scientific discipline of microbiology, and the related chain of events, that has come to be known as the “bacterial revolution”, where the discovery of microscopic beings reshaped the way humans understood the world, industrial processes and even our own bodies.

The “Bacterial Revolution” and the human body *(1860s – World War II)*

The identification and study of the microbe, initiated by Pasteur’s discovery and implemented through his institutes, resulted in a completely new way for humans to understand the world, production and our own health. This shifting understanding and new body of knowledge and practices has come to be called the “bacterial revolution” or “microbial revolution”. While microbes were shaping many industries, including synthetic chemistry and material production, their role and shifting perspectives in the field of medicine is one of the most illuminating, as it showcases forms of intimacy and control like no other.

Bacteriological practices completely transformed the medical conception of disease. Now, with the new knowledge and study of pathogenic microbes, public health could be deduced to addressing a single common enemy who’s “pathogenic power can be tamed by the genius of a few men” (Brives & Zimmer, 2021).

Following this focus on bacteriology in medicine, physicians of the 19th century aimed to protect the human body from external germs, the common enemy capable of penetrating the body in multiple ways. This thinking reinforced the idea of the barrier[15] between the human body and an invisible natural other, now known to be heralding a threat to our most intimate environments. In response doctors zoomed in on specific pathogenic agents under the microscope, as a result narrowing their focus and losing sight of a bigger picture of health, disconnecting health from the environmental context in the shadow of a rationalisation of health purely through the fight against pathogens. Similarly, this zoning in and isolation of bacteria excluded microorganisms themselves from their environment and relationships, positioning them as

[15] See case study: *Environmental Bubble* Ryner Banham: A Home Is Not a House Page 32-33

unitary objects rather than complex living beings.

In this quest to control and eliminate pathogenic microorganisms, Paul Ehrlich pioneered the search for a chemical that would kill a microorganism without impacting its human host. This quest found limited success, until in 1928, a chance event in Alexander Fleming's London laboratory, the discovery of the antibiotic properties of penicillin, significantly changed the course of medicine, and the course of the human-microbe relationship:

> "Alexander Fleming, a bacteriologist at St. Mary's Hospital, had returned from a vacation when, while talking to a colleague, he noticed a zone around an invading fungus on an agar plate in which the bacteria did not grow. After isolating the mold and identifying it as belonging to the Penicillium genus, Fleming obtained an extract from the mold, naming its active agent penicillin. He determined that penicillin had an antibacterial effect on staphylococci and other gram-positive pathogens." (Gaynes, 2017, p. 849).

However, it was not until after the Second World War that penicillin was approved for clinical use, and the 'golden age' of antibiotics profoundly shaped medicine, societies and the "biologies" of the microbes themselves (Landecker, 2016).

At the same time, this idea of synthetic replication was an ongoing topic in the field of chemistry. While synthetic organic chemistry, and the laboratory synthesis of natural resources, was highly admired by the majority throughout the nineteenth century, it sometimes seemed that it could not quite match up to the scale and complexity of nature itself. So, towards the end of the nineteenth century, with a growing understanding of natural products, there was also a growing respect and appreciation for natural products from natural resources (Bud, 1993, p. 12). Through the growing popularity of the 'laboratory for the living organism', coined by English biochemist William Forser, the limits of human chemistry were further and further explored, even though scientifically demonstrations of its potential were reaching new heights. By 1925, the German chemical combine IG Farben proclaimed organic chemistry exhausted and noted that "scholars were turning towards research on natural products" (Bud, 1993, p. 12). This attitude was reflected across the field, with many chemists at the time expressing a growing fatigue for synthetic products, preferring an appreciation for the natural. Wilhelm Koenig, a chemist who was previously deeply involved in synthetic development, developing himself a synthetic replacement for quinine to reduce fever, expressed his attitude towards synthetic organic chemistry through song. The verse, translated freely in Bud's *Uses of Life*, goes as follows:

> *"*Synthetic the coffee, Synthetic the wine
> Synthetic the Milk and the Butter Gloss Shine
> On top of it all, even beer is not pure
> Natural nutrition, you won't find it to be sure
> Then do not let the devil take it for free
> That wretched synthetic-made Chemistry"*. (Bud, 1993, p. 12)*

Koenig's verse clearly reflects a distaste within the field for the rapid development of synthetic products, and a returning appreciation for the natural. However, the rubber shortage at the beginning of the twentieth century called for the development of a synthetic rubber product that enabled a new rapid development of synthetic production processes. In order for the countries at mercy of the Brazilian natural rubber monopoly, producing a synthetic product was the best option to keep up with the development of this crucial material. With this development of synthetic rubber, came the vital connection between synthetic organic chemistry and the work of microorganisms in the biological production of chemicals, the beginning of the "microbial revolution" in industrial production.

At the beginning of the century, rubber production in Europe was dependent on plantations in Brazil and British colonial plantations in Malaysia. The industrial dependence on this resource was highlighted when there was a shortage of raw natural material and critical industries, including the motor car industry, were affected. German and British organic chemists saw laboratory synthesis, which had gained support and popularity in the previous century, as the obvious solution to this problem. By 1909, groups in Britain and Germany were working on developing a process to synthesise a rubbery substance. A breakthrough in this development came with the connection between a team of chemists in Manchester, and the Pasteur Institute, with their work on microbes. With Pasteur's discovery, microbiology was gaining popularity, therefore the idea of connecting these two fields was not hard to sell at the time, and turned out to provide the solution to both a way to utilise wasted hulls of rice produced as a by-product of the manufacture of starch, and to obtain lactic acid from microbial activity which could be turned into the chemicals such as isoprene, which was known to react with itself spontaneously to form a rubbery substance, the initial starting point of this research. Further research at the Pasteur Institute enabled the development of a process which yielded a bacterium that could produce butanol and acetone, from starch. The relevance of butanol in synthetic rubber manufacture became clear with new research published an article in Germany showing that it could produce superior rubber to isoprene. These developments were combined with initial research by the Manchester team's work with isoprene, and together with the inputs from the Pasteur Institute, they had generated a new way to produce synthetic rubber. This had enormous commercial potential, as Bud explains on the work of scientists: "their enthusiasm for profiting from both technology and the publics willingness to believe established a fascinating precedent for the future of biotechnology" (Bud, 1993, p. 41).

Although the need for new materials outweighed the sentiments towards synthetic natural materials brewing at the end of the nineteenth century, and synthetic material production supported by microbiology at the Pasteur Institute, escalated at a rapid scale, similar concerns about synthetic versus natural carried through to debate and speculation within academia. The main topics of this concerned the threat these new materials posed on Britain's growing natural rubber interests in Malaysia. Henry Armstrong, a chemistry professor in London, reflected on this in an article entitled "The production of Rubber: With or Against Nature", where he discussed mainly on the impacts that heavy investment in these synthetic materials would have on colonial agriculture. On this he pondered topics that would resonate through the twentieth century, writing that "we are competing with nature in many directions at present and it is very desirable to discuss whether in the future it will be either desirable or possible to work so much against her" quoted from (Bud, 1993, p. 41). Similar to sentiments of chemists at the time of Foster's 'laboratory for the living organism', Armstrong also wrote about the limitations of synthetic chemistry, and a growing respect for the complexity of nature, "ethically we shall probably be making a mistake in not availing ourselves to the full of the activity of the plant but, apart from this, it may well be that, when everything is taken into account, the plant is able far more effectively than man to make rubber from starch" (Bud, 1993, p. 42).

While this sparked debate and speculation around the scaling up of synthetic rubber production on the basis of a synthetic versus natural debate, the concerned impact on nature was still considered from a perspective of synthetic nature in a sense, where nature is represented through colonial agriculture. Through this perspective, the impacts of synthetic production or working "against nature" are appreciated from a sense of the effect on agriculture and colonial development, therefore reflecting still a commitment to the human agenda rather than intrinsic care for nature itself. However, such debates of "with or against nature", and the growing respect for nature and its complexity are important factors still in current human-nature relationship discourse.

With the declaration of the First World War, acetone, another product of Fernbach's butanol process, came into high demand as it was an essential solvent for explosives. While Fernbach's factory failed to perform in meeting demands, Chaim Weismann had identified his own bacterium which could ferment starch more efficiently to acetone and butanol than Fernbach's. This so-called Weismann process commercialised quickly, and in this upscaling process which required "a new degree of microbial sophistication in manufacture" (Bud, 1993, p. 44) as the process required and developed a new sterilisation and laboratory standard at an industrial scale. This was a critical turning point in the history of biotechnology, with large industrial scale use of microbes in controlled environments now a viable option for production of chemicals and synthetic materials. This sense of control remains in the use of microorganisms in industry today, while critical in standardising processes in order to achieve an end result, and making the scaling up of production possible, it is eerily reminiscent of an attitude of controlling nature which developed due to human-centralism resulting from rationalist thought as far back as the Scientific Revolution. This proves a very interesting debate when analysing current day biomaterials using microorganisms in this human-nature relationship line of thinking.

After the First World War, Weismann plants in the US and Canada were reborn in a new consumer world, now with its original product butyl alcohol being useful in lacquers for the booming motor car industry, and production continued to increase. Sentiments for the proper use of biological resources remained still, with William Pope asserting that rubber, and other natural products, would be better grown than made, and that "Britain should not follow Germany's lead in attempting to replace natural products" (Bud, 1993, p. 46). Pope also shared beliefs in line with a developing approach in the biochemical industry that resources such as oil and coal should be processed rather than burnt, leading to an emphasis on circularity and resource renewability suggestive of the self-contained systems-thinking and waste management design to follow.

Antibiotics and antimicrobial resistance: shaping biologies *(World War II-2000)*

The commercialisation of antibiotics, set off by the discovery of penicillin mold, profoundly changed society. Post World War II, with the weapon of vaccines and antibiotics, was a growing faith in the eradication of microbes, the common enemy to public health. These antimicrobial tools provided "powerful technoscientific means of controlling and stabilising the consequences of microbial exchanges generated by increasing urbanisation, colonisation and commercial globalisation" (Brives & Zimmer, 2021). Rather than dealing with the cause of the problem, and the ignored environmental conditions, we could eradicate and fight against and thereby gain control over, a single and common enemy in the form of pathogenic microorganisms. Therefore, antibiotics and vaccines, although we are undoubtedly grateful for them in many ways, were naively glamorised as a magic bullet to deal with the rising problems caused by our own uncontrollable growth.

However, this 'golden age' was followed by a gradual decline in development and faith, and a growing antibiotic resistance in many pathogens, which has led to the current antimicrobial resistance crisis as bacteria evolved and adapted to our attempts to eradicate them. More recent literature highlights more directly the consideration that "microbes continue to flout the systems set in place to try to control them" (Brives & Zimmer, 2021) but the ambivalence and adaptability of microbes was noticed and documented over the course of historical interactions, particularly here with the use of antibiotics in this battle between humans and pathogens. The science historian Hannah Landecker describes how the invention, industrial production and massive use of antibiotics has not only shaped societies but has irreversibly changed the biology of the microbes themselves[15]. Now, not only are we tracing a history of biology, but a "biology of history" whereby we can observe the physical traces of human activity on microbial life (Landecker, 2016). This "biology of history" was also beginning to be observed on a macro scale, with the growing awareness of environmental conditions resulting from human growth and development, or as we have now come to more

[15] See case study: *Silk I & Silk II*
Neri Oxman
Page 46-53

commonly discussed as the Anthropocene epoch. This goes to show how deeply human activity and careless economic growth have impacted the earth's systems, species and environments, as well as the intricacy of microbes and their interaction with other beings and the environment.

It was not until the 1980s that groups representing an "ecological vision" characterised by "a consideration for the relationship between disease, environmental and evolutionary process" (Brives & Zimmer, 2021), an evolved understanding based on Haeckel's definition of ecology, emerged from the minority to help explain the emerging antibiotic resistance. In this time, Bruno Latour played an influential role in rethinking the existing notion of the microbial or bacterial revolution through human-centric approaches, to viewing it rather from the perspective of the microbes themselves. He understood and described microbes as useful socio-technical objects to link the specialised and discrete laboratory cultures to the larger context of European, American and colonial societies (Latour, 1984). Through this understanding, in his later book *The Pasteurisation of France*, Latour tracks a microbial history of the politics of the accommodation of microbial life into social life in parallel to the history of politics of battle. He emphasises that science cannot continue to be understood as independent and separate for society and that "we have to give evidence that "science" and "society" are both explained more adequately by an analysis of the relations among forces and that they become mutually inexplicable and opaque when made to stand apart" (Latour, 1988, p. 7).

Similarly, biologist Lynn Margulis approaches microbes in the 1980s with admiration, having demonstrated in her work with James Lovelock, the fundamental role of microbes in the metabolic regulatory processes that govern the evolution of living organisms (Brives & Zimmer, 2021). Lynn Margulis's work was influential in questioning the rigidity of the barrier between species, one previously reiterated in the perception of public health. She offered new was of interpreting the evolution of living organisms, through a process of endosymbiosis, or in other words by a fusion or internalisation of one organism by another (Margulis & Sagan, 1986), as opposed to an independent battle of the fittest as described by Charles Darwin.

Through these changing perspectives on microorganisms and their relationship to context and ourselves explored at the end of the twentieth century, came the arrival of a revised understanding of biology and a conscious reassessing of how we understand and relate to nature with more plurality and less boundaries.

The "microbial turn"? *(2000-now)*

With the turn of a new century, the newly developed methods and technologies of metagenomics enabled the sequencing of genetic material of microorganisms recovered directly from their environments, rather than relying on out of context cultivation-based methods. This technique has enabled a far deeper understanding of the previously hidden diversity of microscopic life, and therefore led to new knowledge and appreciation of the role of microorganisms in the make-up of all aspects of the environment.

With this new previously invisible diversity and set of relationships becoming visible, along with the discourse emerging with the ecological vision of the 1980s, we as humans have been forced to rethink our predetermined classification criteria, not only of these newly discovered microscopic organisms, but of the ecology of macro-species and our own sense of self. This thinking led to a new view of organisms and ecosystems in which "microorganisms no longer seen as discrete and individual entities but as multispecific and symbiotic complexes: endlessly renewed assemblages of more or less sustained interactions and associations amongst several species**[16]**, in which microbes play various roles at different levels" (Brives & Zimmer, 2021). This species of relationships has more recently come to be known as a

[16] See case study: *Feral Surfaces*
Harrison Atelier
Page 54-59

"holobiont" (Gilbert & Tauber, 2016).

In other words, microorganisms have begun to reveal to us the complexities and intricacies of interspecies relationships, and questioned our very understanding of evolution and individuality, as defined previously by the likes of Darwin. Heather Paxson is an influential figure in this discourse, writing on what she defines as "microbiopolitics"[17], or "the creation of categories of microscopic biological agents; the anthropocentric evaluation of such agents; and the elaboration of appropriate human behaviors vis-`a-vis microorganisms engaged in infection, inoculation, and digestion" (Paxson, 2008, p. 17) as a way to reflect on how we as humans live with microorganisms thereby reflecting how humans ought to live with one another. She explains:

> "If philosophical attention to microbes—and more, to how microbes and humans have been companion species (cf. Haraway 2003)—might "lead to a better understanding of how human health, disease resistance, development and evolution have depended and continue to depend on interactions with microbes" (O'Malley and Dupr´e 2007:158), then anthropological attention to microbes might lead to better understanding not only of certain human cultural artifacts—"natural" foods, for instance—but ultimately of the central object of our study: anthropos, the human itself." (Paxson, 2008, p. 19)

Paxson defines this type of thinking in reference to the changing human-microbe relationship in cheese production as "post-Pasteurian cultures", resisting the "hyperhygenic" vision of the "Pasteurian world" (Paxson, 2008), or the world dependent on antibiotics and resisting germs and bacteria in the name of public health. As previously discussed, in the post-war "bacterial revolution" the quest to eradicate pathogens defined public health practices, not only in physiology itself, but also in food practices. According to Paxon, these "Pasteurian practices" in food production, similar to antibiotic practices in the medical field, "configure microbes as elements to be eliminated so that human polities might be cultivated" (Paxson, 2008, p. 17).

In 2014, Paxson and anthropologist Stefan Helmreich introduced a more multidisciplinary concept to explain this changing perception and relationship: the "microbial turn" (Paxson & Helmreich, 2014). Building on this, Jamie Lorimer proposed another, even more interdisciplinary concept of the "probiotic turn", in response to the antibiotic tendencies of the previous century, which aims to describe human interventions that use life to manage life (Lorimer, 2020). The expanding of the extent of such explanations to other disciplines draws attention to "ways of renouncing the domination and control of ecologies" (Brives & Zimmer, 2021) as a multidisciplinary approach.

Through the COVID-19 pandemic of 2020, microbes reinforced their power to shake up the operation of our societies, reminding us that we are not the only players, and we do not always have the power to control. This discussion, that humans on not the only ones that make up society, was by this time firmly anchored in literature of humanities and social sciences, yet we still struggle to be exposed to our own weakness and vulnerabilities. Therefore, the majority fell back to trusted techniques of keeping the microbe out with masks, gloves, hand sanitiser and vaccines defining the way we live our lives. It is still debated between those following probiotic and antibiotic tendencies what the right thing to do was in the greater picture of public health when human lives are on the line. From a non-human perspective, it was also observed that the planet responded well to our reduced movement and activity, which leads one to ponder, with probiotic theory circulating in the background, whether the microorganisms we deem as the enemy to public health are actually fighting for and working symbiotically to protect the greater ecosystem of the planet against the attacks of the capitalist society, a common enemy to the planetary health. What is clear here however, as pointed out by Brives and Zimmer, is that the global pandemic "tended to relativise the scope and

17
See case study: *In Vivo*
Bento & Vinciane Despret
Page 68-75

content of this ‘microbial turn’, or at least would lead one to observe first and foremost that it does to seem to apply across the board to all relationships between humans and microbes” (Brives & Zimmer, 2021).

While it is debated whether it is appropriate to define this as a “turn”, it is true that we are beginning to see a substantial shift in the way that humans and microbes interact, and the agency given to each in the process. This shift has been critical in the development of building materials reliant on the metabolism of microorganisms, as previous conceptions of bacteria and fungi could never have enabled the space for this type of thinking to be explored. These developments were also made possible by technological developments in seeing and studying microscopic beings, which made it possible for us to understand their internal processes to be able to tap into their benefits[18].

However, this study hopes to evidence that with an understanding and appreciation the role of microorganisms in the make-up of the natural environment, and all life on earth, we open ourselves to boundless opportunities for learning and re-imagining the way in which we occupy and interact with our environment and collaborate with nature going into the future. Our relationship with microorganisms through this perspective has inspired us in many ways to critically reflect on our sense of self to begin to mend our relationship with nature, across all scales.

18
See case study: *Bioconcrete*
GXN, BioMason, Silas Inoue
Page 76-83

3. THE MATERIALS

Assessing biocement and mycelium composite products
as alternatives to conventional materials through
technical and environmental comparison

3.1. **Material Introductions**

In order to perform a more specific technical, environmental and legislative analysis on biocement and mycelium composite materials, I will be referring mainly to specific products which are currently on the market. By choosing to use specific and available product examples one is able to gather more specific data for real world applications. This way I will also be able to get a better understanding of where the material stands within a legislative framework from a technical and environmental perspective, and what standardised and comparable documentation and declarations are available within such existing framework and beyond. I will also supplement this information where needed with reference to scientific research to gather a comprehensive understanding of the current and future prospects for these novel materials. The producers and products that I will focus on are:

Biocement

BioMason: BioLITH tile
Prometheus Materials: ProZero Masonry Unit Solution
Basilisk: Healing agent (HA) additive & Self-Healing Repair Mortar MR3

Mycelium Composite

MycoHAB: MycoBlock
Ecovative Design: MycoComposites 027, 584 & 570
Mogu: Acoustic panels & Foresta System

For control, I will be referring to EN and ASTM standards, product data sheets and both sector and specific product environmental product declarations (EPDs) for standard construction units available and widely used within the mainstream market including:

Conventional Materials

CEM I Ready-Mix Concrete (Sector)
CEM I Standard Concrete Masonry Unit (Standards)
Clay Brick (Wienerberger)
Expanded Polystyrene insulation (Standards, Sector, BEWI)
Glasswool insulation (Standards)

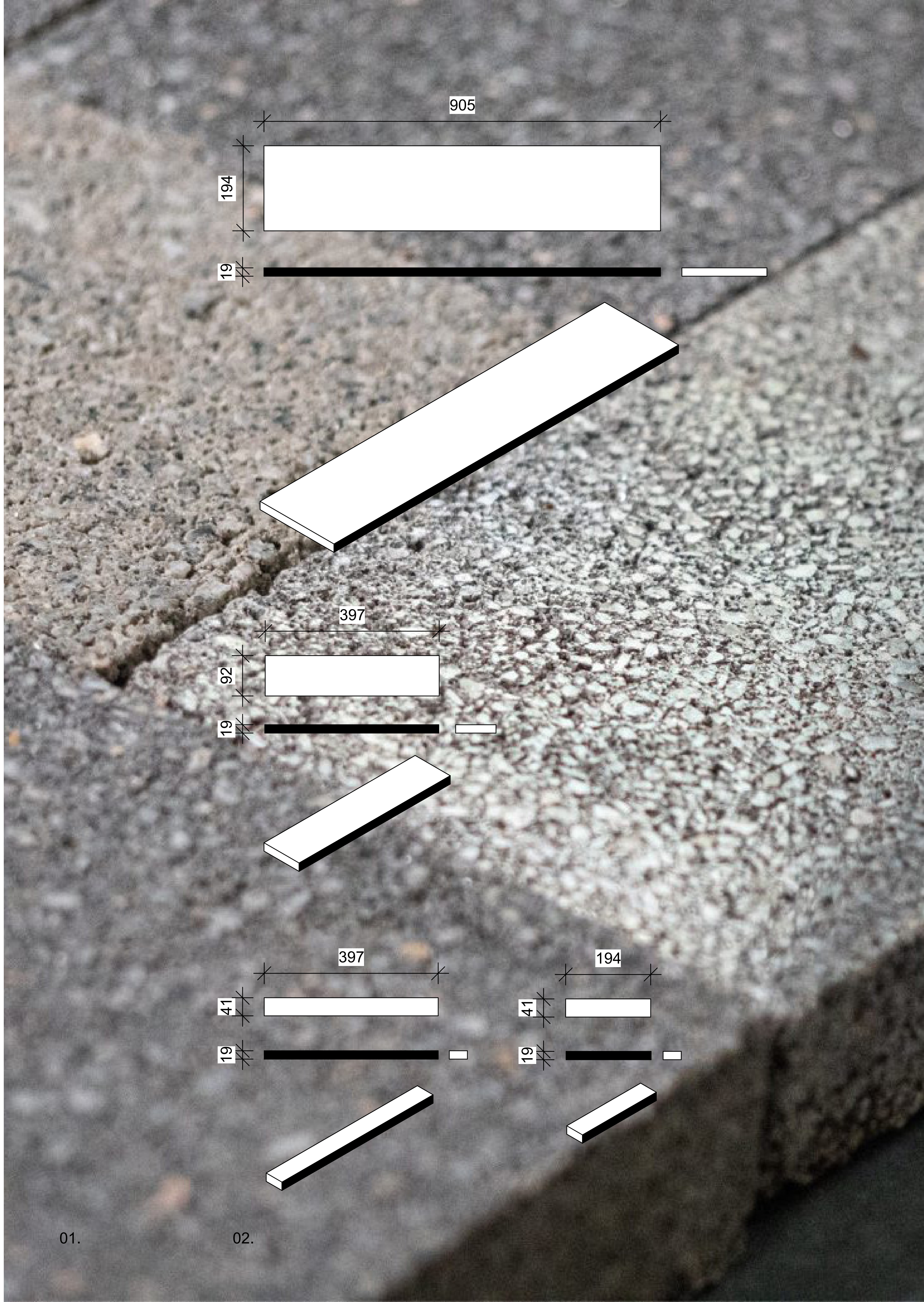
BioMason - BioLITH Tile

Key words: *biocement, bacteria, tiles, paving*

The US based biocement company BioMason is a pioneer in the field of biocement. After the company was established in North Carolina in the United States in 2012, they released their first commercially available product, the BioLITH tile, to market in the early 2020s. The BioLITH tile is also supported in the Netherlands by FRONT material suppliers, formerly StoneCycling, and produced in the Denmark in BioMason's Biobeten factory, in conjunction with IBF, the largest producer of precast concrete in Denmark (BioMason).

Figure 01. *BioLITH tiles in pepper:* in place at Dropbox showing materiality

Figure 02. *Plan, elevations and axonometric views of available BioLITH tiles:* sising with specific dimensions. Drawing by author, 2024



The tiles are manufactured from waste stream aggregate, 85%, and a biologically generated calcium carbonate biocement material, 15%. They are formed by vibratory compaction in a semi-dry mix and cured in ambient temperatures, reaching full strength in less than three days (BioMason). Due to this process and the metabolism of microorganisms, the production does not require a kiln or high temperatures, and therefore much less energy and resulting emissions to produce. On top of this, the tiles are able to sequester carbon dioxide (CO_2) from industrial sources up to 44% of the mass of the product (Stone Cycling).

The tiles are appropriate for exterior and interior use in commercial, institutional, and residential building projects. The units can be installed vertically in vertical facing assemblies or installed on a support wall with adhesive systems, and horisontally on a substrate.

The tiles are available in a range of colours, a medium grey, a neutral earth tone labeled ‘ginger’ and a dark grey labelled ‘pepper’. As the biocement material itself is translucent white in color, the colour of the products is due to the different aggregates used.

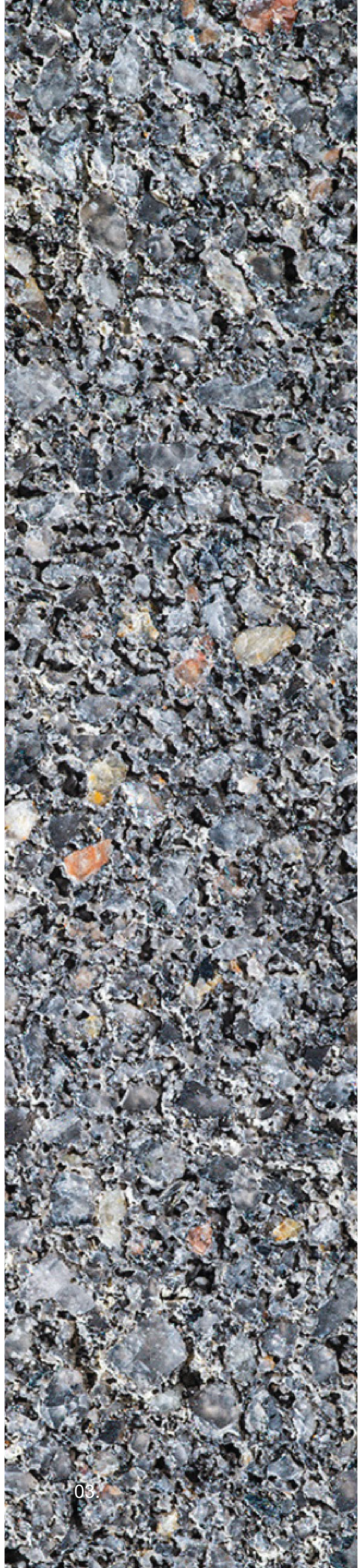
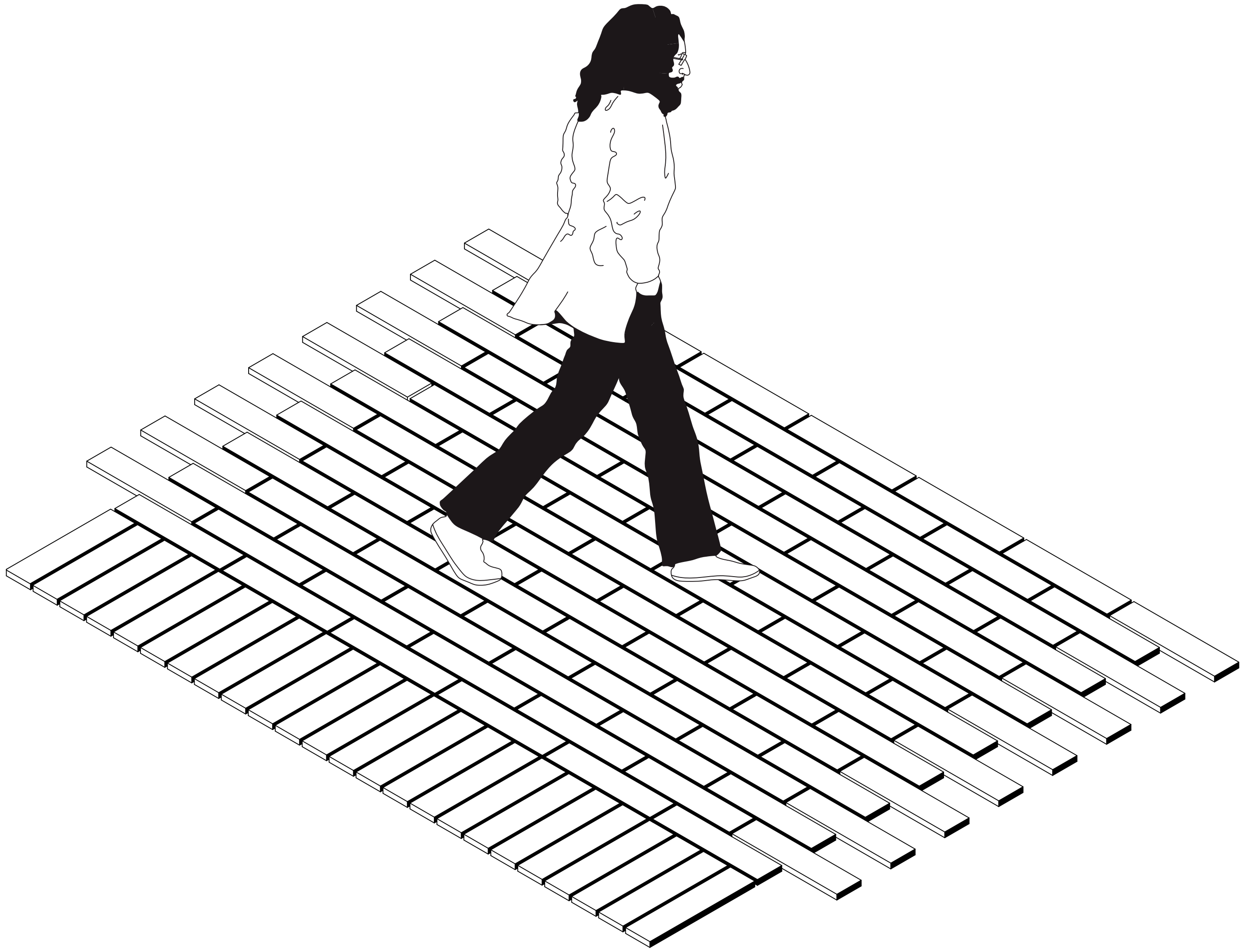


Figure 03. *BioLITH tile medium grey*

Figure 04. *BioLITH tile natural*: also called ‘ginger’ or ‘sand’

Figure 05. *BioLITH tile pepper*

06.



BioMason has completed installations in building projects for large corporations across America and Europe including:

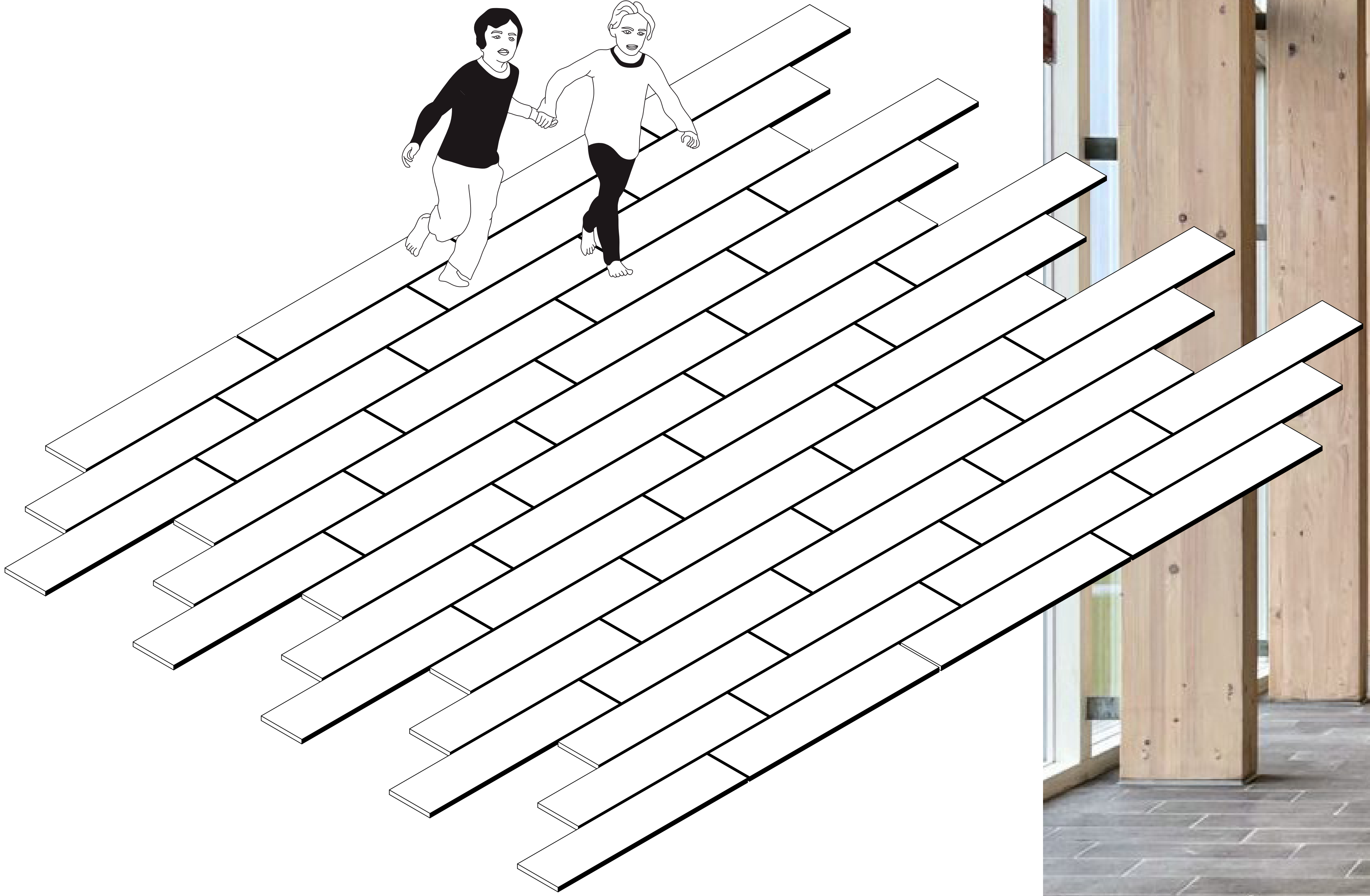
1. Dropbox Headquarters, San Francisco:
   In their first ever commercial installation, BioLITH tiles were used in the exterior courtyard of the tech company's headquarters.

Figure 06. *Exploration of BioLITH tile arrangement as installed at Drobpox Headquarters*: the first commercial application. Drawing by author, 2024

Figure 07. *BioBasedTiles at Dropbox*: BioLITH medium grey tiles being installed at Dropbox Headquarters

07.

08.

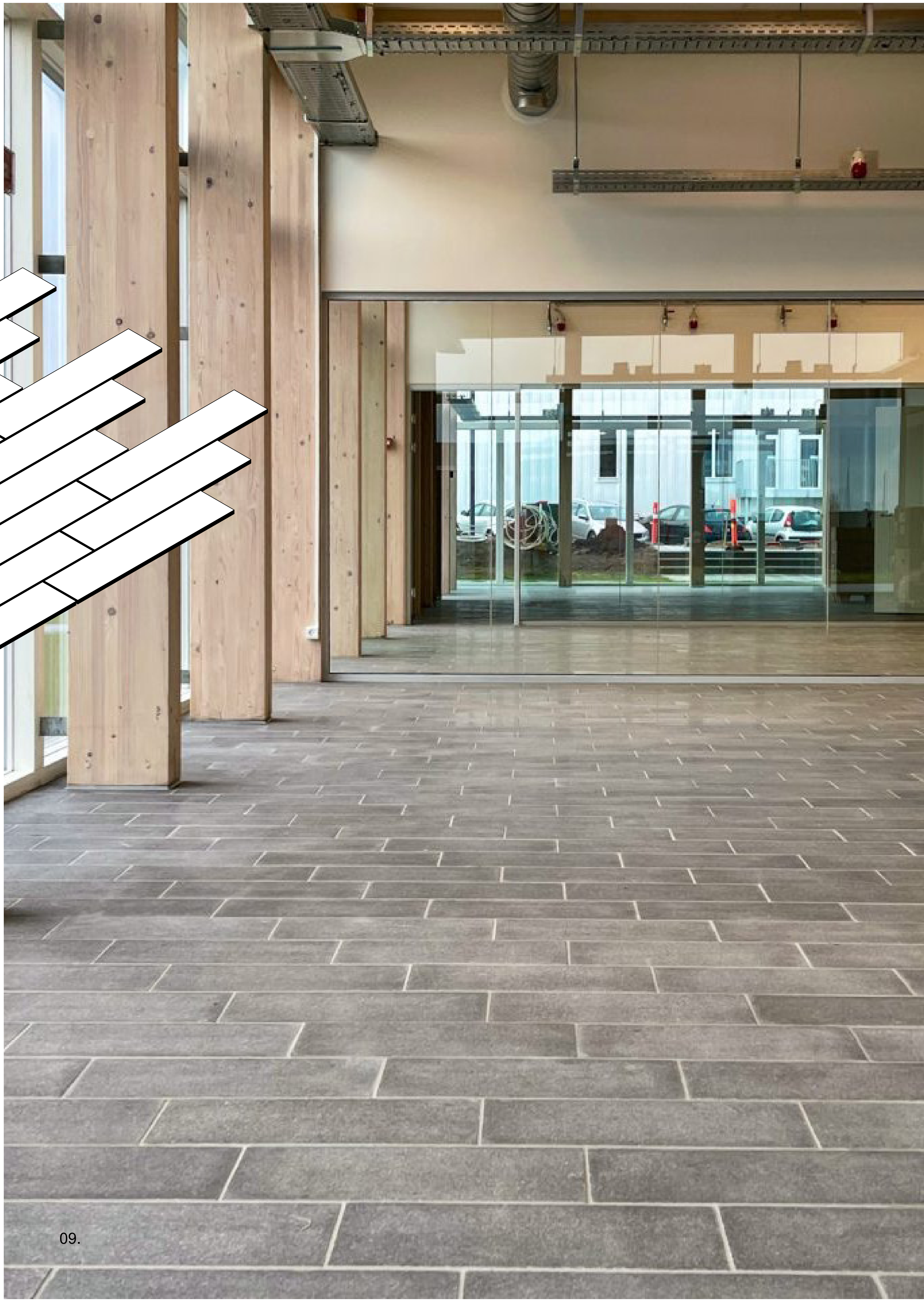


2. Helix Lab, Denmark:

First European installation, where the pepper honed BioLITH tiles were used for the building's flooring. Along with the use of BioLITH tiles, the project was also built using solid wood for its load bearing structures and facades, further reducing the environmental impact of the project as a whole in terms of carbon emissions.

Figure 08. *Exploration of BioLITH tile arrangement as installed at Helix Lab:* the first European installation. Drawing by author, 2024

Figure 09. *BioBasedTiles installed at Helix Lab:* BioLITH medium grey tiles in place at Helix Lab



09.

Prometheus Materials - ProZero Masonry Unit

Key words: *biocement, cyanobacteria, masonry units*

The products produced by Boulder, Colorado based company Prometheus Materials utilise microalgae as an alternative to carbon-intensive portland cement. The advantage of using microalgae is their ability to photosynthesise and use carbon dioxide waste streams as a valuable production input. The company was founded in 2021, and developed their work based on research conducted by a team of biotechnology and engineering professors at the University of Colorado Boulder in response to a Department of Defense Engineered Living Materials (ELM) program which looks to living materials as a way to support military logistics and construction in remote, high-risk or post-disaster settings through in-situ and adaptable methods[19].

ProZero Bio-Block Masonry Unit Solution

The company is currently producing concrete masonry units (CMUs) using their microalgae-based method. While the CMUs are the only currently available product, they claim to be developing more products including pre-cast and ready-mix products.

ProZero Acoustic Panel Solution

Prometheus Materials is also in the testing process of utilising their product in the form of acoustic panels as it was noticed that their existing bio-based CMUs dampened sound more than regular concrete.

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[19] Note: This is an ongoing topic of discussion in engineering departments across universities

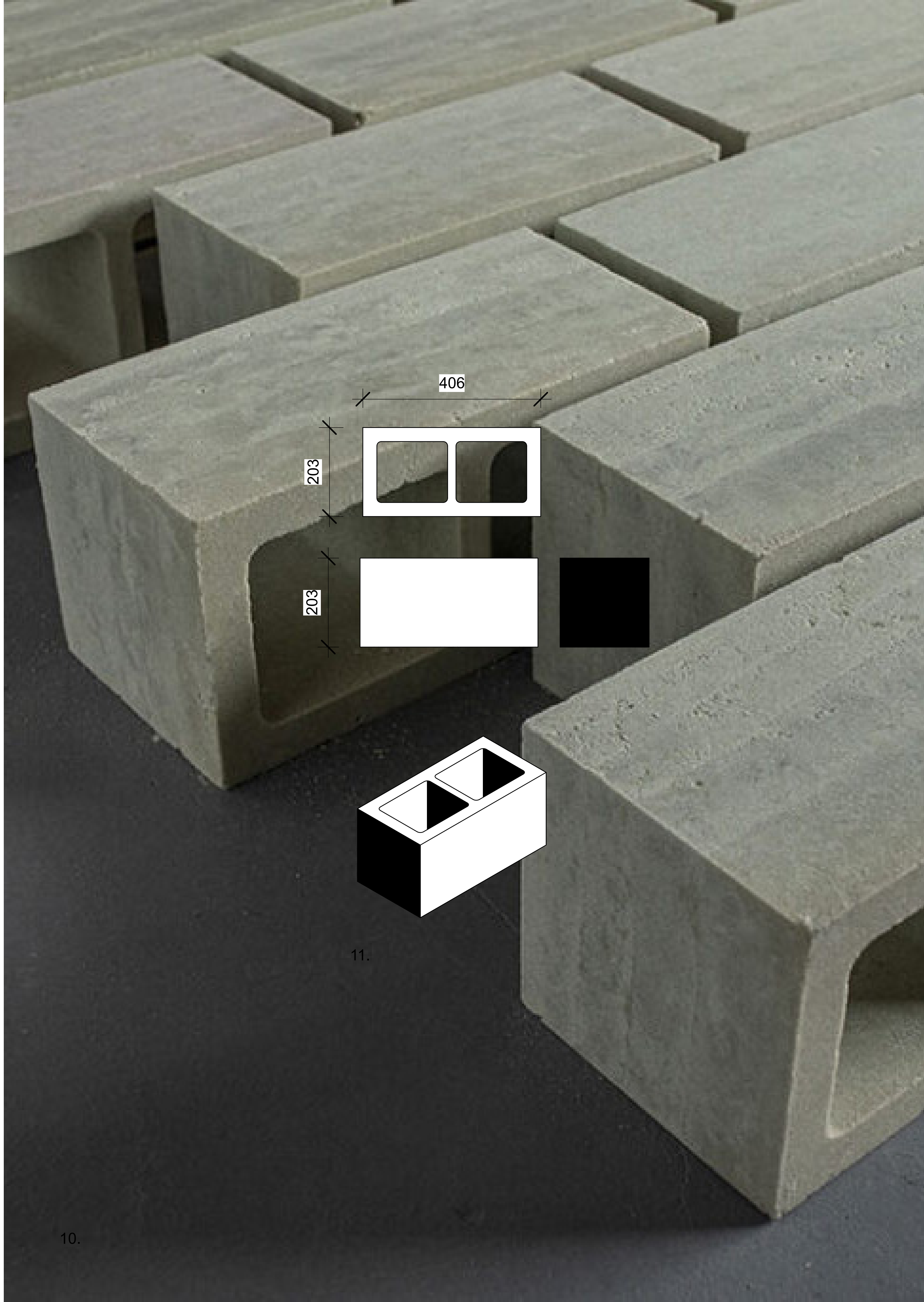

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Figure 10. *Prometheus Materials masonry unit solution:* laid horisontally on the ground

Figure 11. *Plan, elevation and axonometric drawings of Prometheus Material's concrete masonry unit:* Drawing by author, 2024
Note: dimensions are estimated from standard masonry units and images

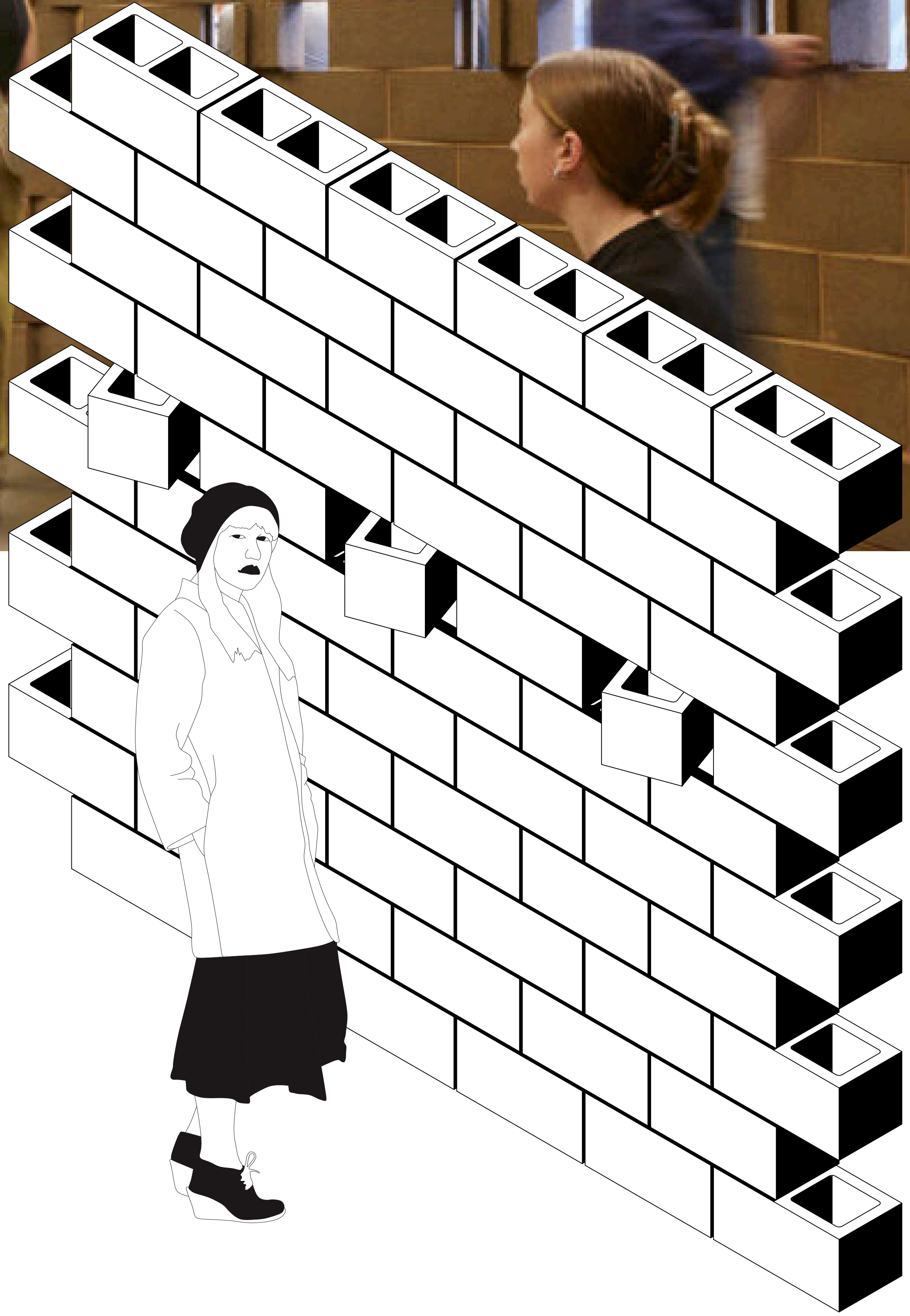
12.

While units have not been used in commercial applications, they have been utilised in pilot projects such as the Bio-Block Spiral.

Showcasing Prometheus Material’s masonry units, SOM’s Bio-Block spiral, showcased as part of the 2023 Chicago Architecture Biennial, is designed as a public gathering space to showcase the versatility, practicality and simplicity of the biocement masonry unit solutions. This is the first public application of this product, still to be fully implemented into common practice.

Figure 12. *Bio-Block Spiral at Chicago Biennale:* Prometheus Material’s concrete masonry units installed by SOM in the Bio-Block Spiral as part of the 2023 Chicaco Architecture Biennal

Figure 13. *Axonometric drawing of Prometheus Material’s concrete masonry units as installed in the Bio-Block Spiral:* showcasing masonry construction typology. Drawing by author, 2024



13.

Basilisk -
Self healing agent and mortar

Key words: *biocement, bacteria, self-healing, admixture*

Basilisk, a Netherlands based company, produces bio-based self-healing concrete products, through a technology invented by Professor Dr. Henk Jonkers at the Technical University of Delft. The products aim to increase functional performance of materials using living organisms, and similarly decrease the environmental impact.

Healing Agent Admixture

The basis of their products is a bio-based granular healing agent admixture, which can attribute self-healing properties any regular concrete. The admixture utilises the metabolism of bacteria to improve the performance of concrete in terms of waterproofing, shrinkage and reinforcement reduction, reduced carbon dioxide footprint and a longer service life. Once activated, the bacteria are able to produce calcium carbonate to seal cracks up to 1 mm (Basilisk).

Self-Healing Repair Mortar MR3

Along with a self-healing agent admixture and liquid repair system, Basilisk provides a self-healing repair mortar, intended for the repair of existing concrete structures. The mortar is composed of portland cement, limestone powder, fly ash, biodegradable polymeric mineral precursor compound, bio-based enzymatic catalyst and selected aggregates and additives, sold in a powder format that is ready to be mixed with water.

The products provide an opportunity for infrastructural applications to improve durability of tunnels, bridges, reservoirs and more.

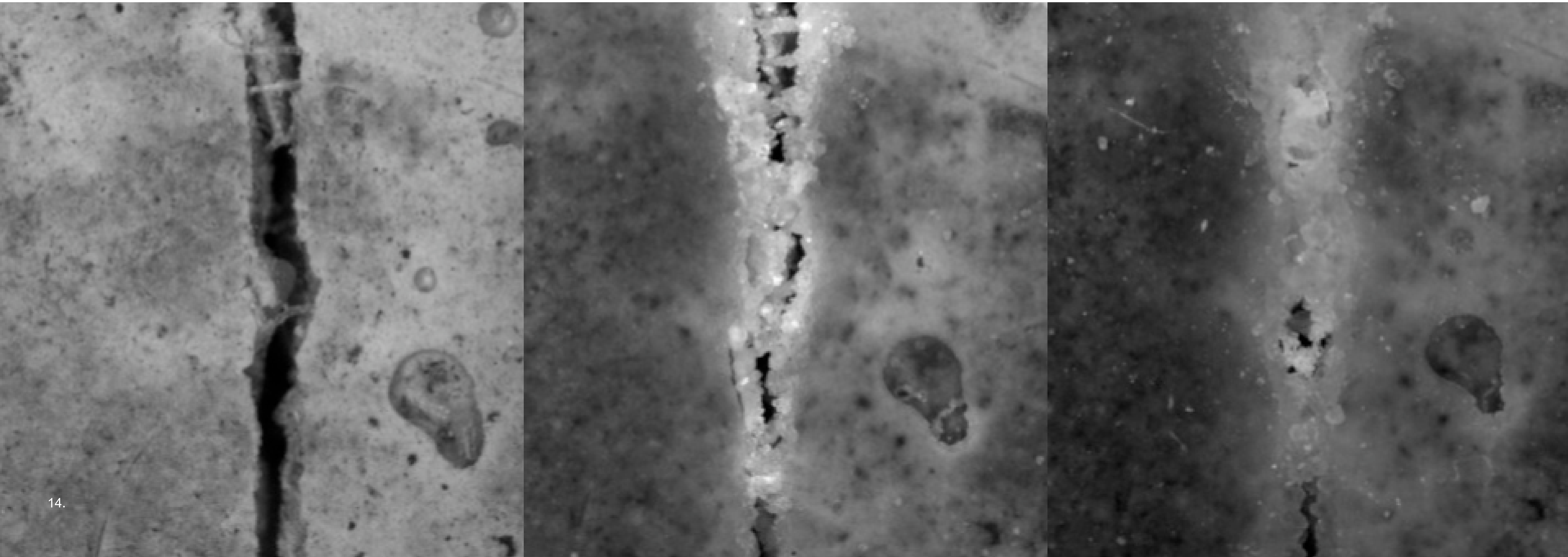


Figure 14. *Bioconcrete healing itself*: stages of self-healing in concrete crack by Basilisk's biological healing agent

Ecovative Design - MycoComposite materials

Key words: *mycelium composite, styrene, panels, packaging, waste, biodegradability, grow-it-yourself*

Evocative Design is a pioneering company in the realm of biomaterials, particularly through its research and development of mycelium-based products. The company has been working on researching and developing mycelium materials for fashion, packaging, food and construction.

MycoComposite 029

These products use hemp herd as a substrate. Ecovative Design has directed most of their focus for MycoComposite materials towards developing a mycelium composite as a replacement for Styrofoam packaging, however this MycoComposite also has uses in the building industry due to its flame-retardant, insulation and noise-dampening benefits which similarly make it a suitable comparison for EPS insulation and acoustic paneling. While this is the composite which has the most development, Ecovative Design has also developed different composites targeted towards the construction sector including the 584 and 570.

Figure 15. *MycoComposite Panels stacked:* Ecovative Designs MycoComposite panels stacked side by side showing texture

15.

16.

17.

MycoComposite 584 Panel

Ecovative Design’s acoustic MycoComposite panels are made by inoculating different substrates with mycelium. The 584 panel uses aspen shavings as a substrate which make it the most suitable for partitions and acoustic panels with high noise reducing properties and low thermal conductivity.

Ecovative Design MycoComposite 570 Panel

The 570 panel uses aspen chips as substrate creating a denser product which gives it stronger mechanical properties.

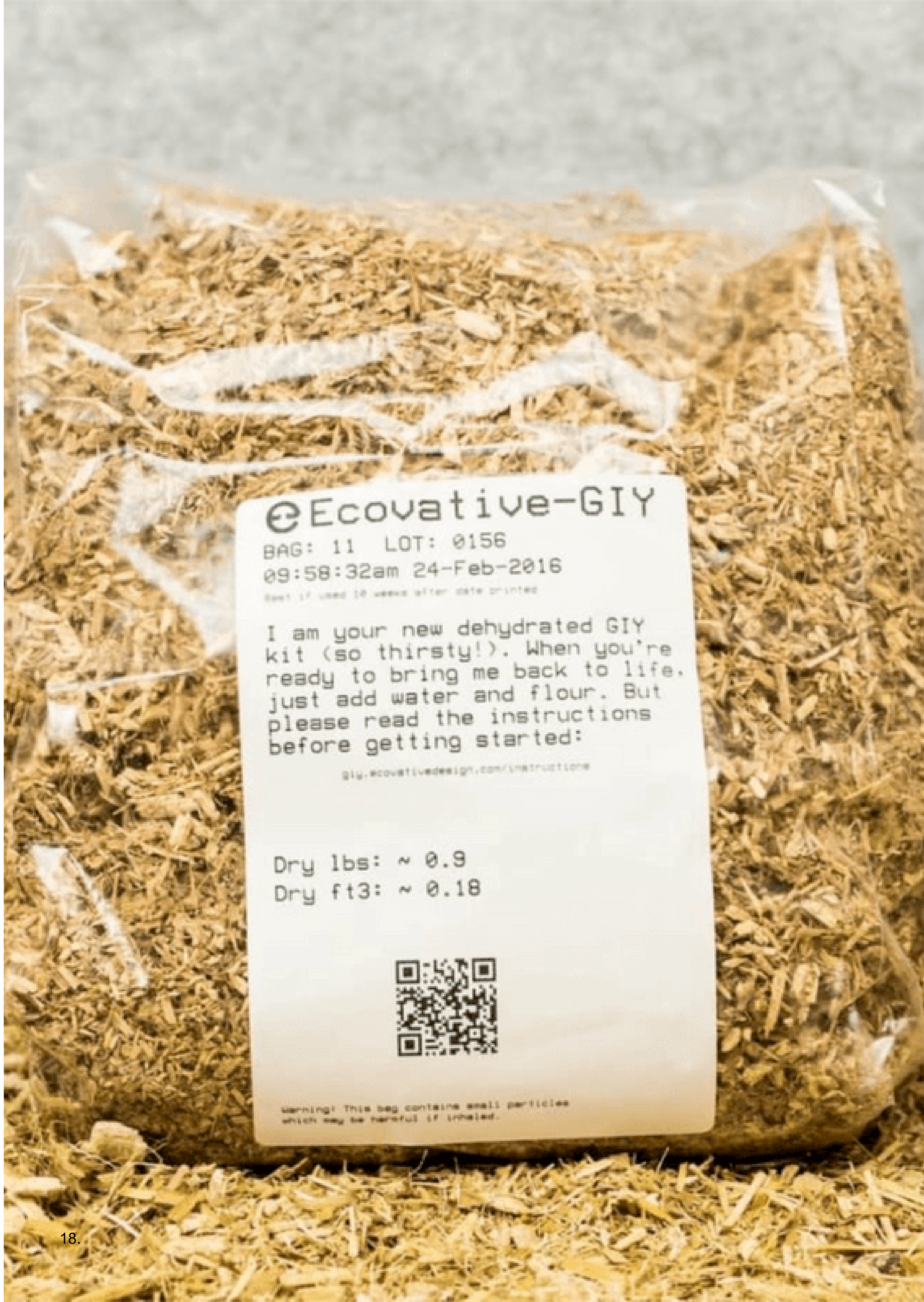
GIY Kits (grow.bio)

Ecovative Design’s spinoff Grow.bio sells grow-it-yourself mycelium composite kits which help spread knowledge and foster creativity in the field of mycelium composite products. The packaging acknowledges the agency of mycelium in the production process as a fun and engaging marketing tool to establish connection with product.

Figure 16. *MycoComposite panel texture*: before aditional growth phase

Figure 17. *MycoComposite component texture:* after aditional growth phase

Figure 18. *Ecovative-GIY kit packaging:* substrate represented through a GIY kit to enable the growth of mycelium composites at home, with message from the myelium itself.



Ecovative-GIY
BAG: 11 LOT: 0156
09:58:32am 24-Feb-2016

I am your new dehydrated GIY kit (so thirsty!). When you're ready to bring me back to life, just add water and flour. But please read the instructions before getting started:

giy.ecovativedesign.com/instructions

Dry lbs: ~ 0.9
Dry ft3: ~ 0.18

Warning! This bag contains small particles which may be harmful if inhaled.

18.

MycoHAB - MycoBlocks

Key words: *mycelium composite, structural, ecosystem, food , waste, resource*

MycoHAB is an innovative foundation with the aim of “addressing food security, generating sustainable building materials, fostering job creation, and promoting a carbon-negative ecosystem by harnessing the power of mycelium technology” (MycoHAB, 2022). After starting as a collaboration between Standard Bank Group (SBG), Massachusetts Institute of Technology’s (MIT) Center for Bits and Atoms and Redhouse Studio architecture firm, MycoHAB now operates independently, researching, developing and practicing innovative ways to use mycelium technology to support communities in Africa and abroad without compromising the environment.

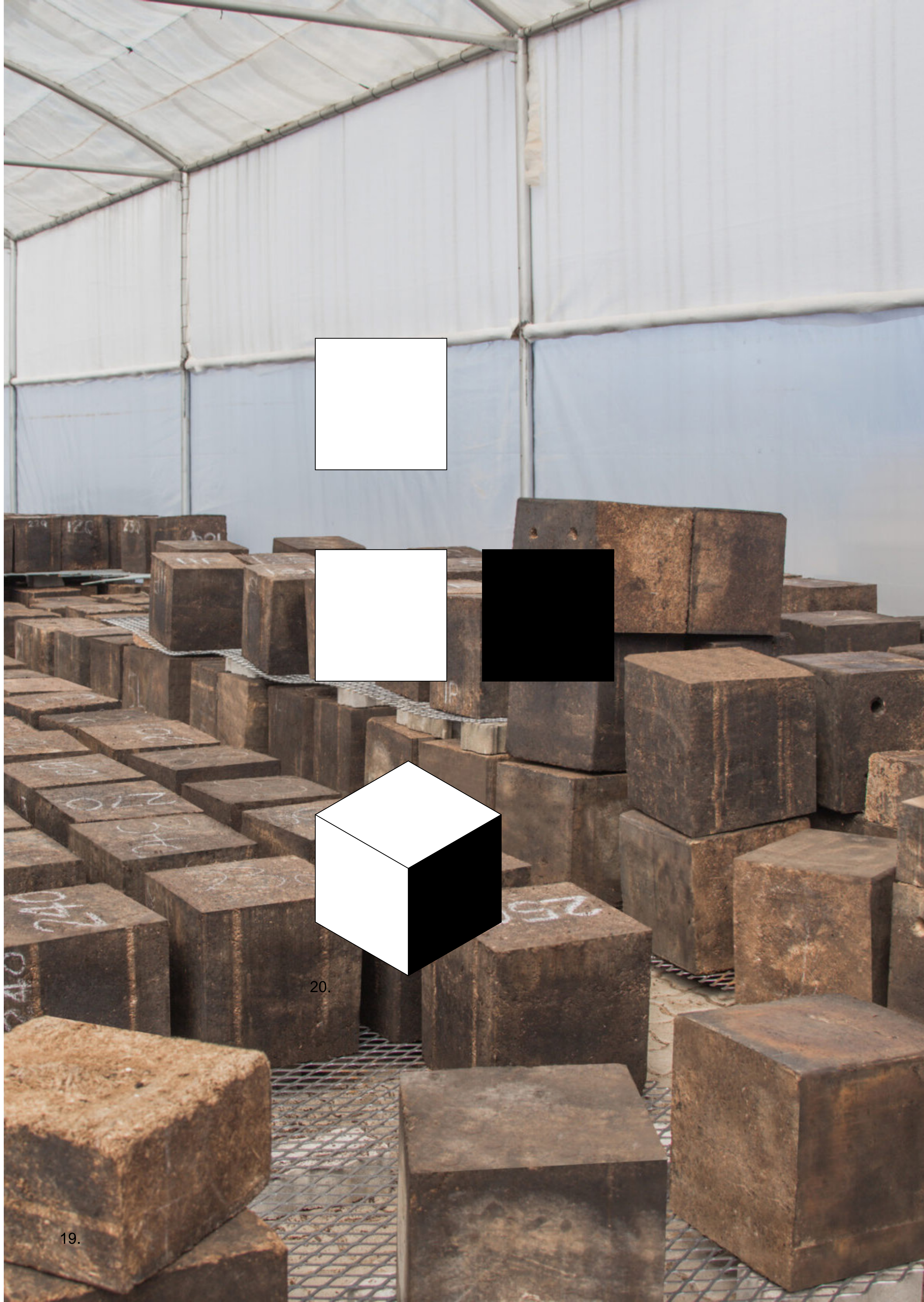


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Figure 19. *MycoHAB MycoBlocks:* prepared MycoBlocks in storage ready to be used

Figure 20. *Plan, elevation and axonometric view of MycoBlock:* Drawing by author, 2024
Note: there is no available information on exact dimensions therefore data has been excluded from this drawing. Estimated sise is between 250 mm and 500 mm square

21.

22.

MycoBlocks

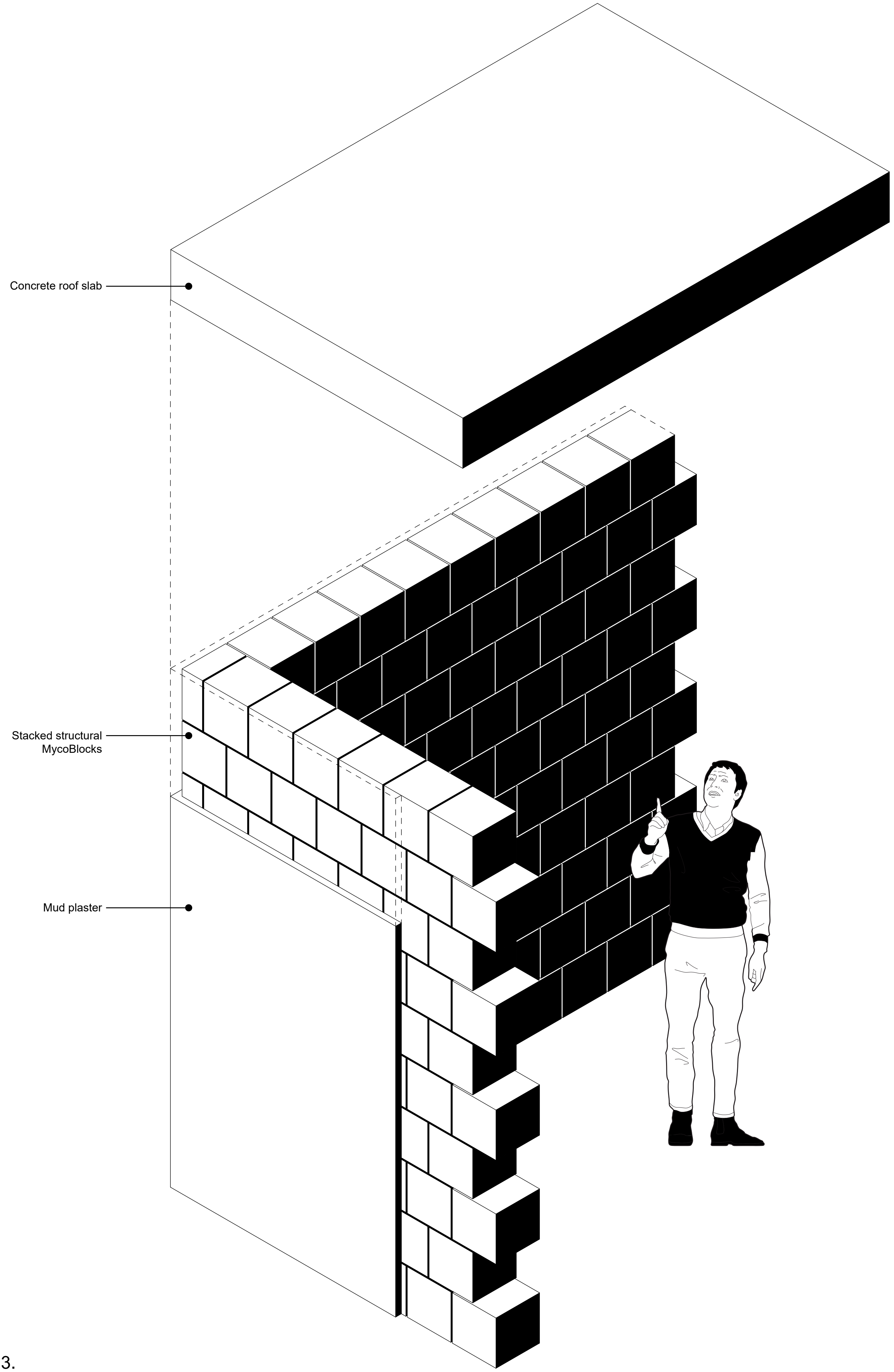
Their project in Namibia combines food production with addressing the housing crisis. Using the destructive encroacher bush, *Acacia mellifera*, as a substrate, they are also assisting in remediation of the local environment. Once the edible mushrooms are produced and sold to local retailers, markets and hotels, the 'waste' or mycelium inoculated substrate is compacted and fired into MycoBlocks which can be used to construct affordable housing. In 2020, the MycoHAB site outside Windhoek, Namibia started operations, harvesting approximately 10 kilograms of mushrooms a week. Now it is estimated that production is over 14 times these numbers (MIT Management Executive Education, 2024).

In the beginning of 2024, an entire house, the MycoHouse 1.0, was built using these MycoBlocks, which has been named the "world's first structural mycelium building" (MIT Management Executive Education, 2024).

Figure 21. *Construction process of MycoHouse 1.0:* the first cosnstruction from structural mycelium.

Figure 22. *Completed MycoHouse 1.0:* constructed from MycoBlocks with mud plaster with concrete and steel roof.

Figure 23: *Axonometric drawing of MycoBlocks as constructed in MycoHouse 1.0:* showing structural arrangement. Drawing by author, 2024



23.

Mogu - Acoustic panels and systems

Key words: *mycelium composite, accoustic, interior, treatment, assembly*

24.

25.

Mogu is an Italian biodesign company which has developed innovative mycelium-based materials for interior design and acoustic purposes, combining technical properties with innovative aesthetics.

Mogu Acoustics

Mogu Acoustic panels are made using upcycled textile residue and fungal mycelium. These are the first commercially available products of their kind. The range includes different shapes and dimensions including the wave, kite, fields and plan rectangular components which each have unique dimensions and acoustic properties.

Figure 24. *Myceloum acoustic panel 'wave'*

Figure 25. *Mycelium acoustic panel 'kite'*

Figure 26. *Mogu acoustic panels:* wave panel installed on a wall

Figure 27. *Plan, elevations and 3D of Mogu wave panel:* Drawing adapted by author from Mogu resources, 2024

27.

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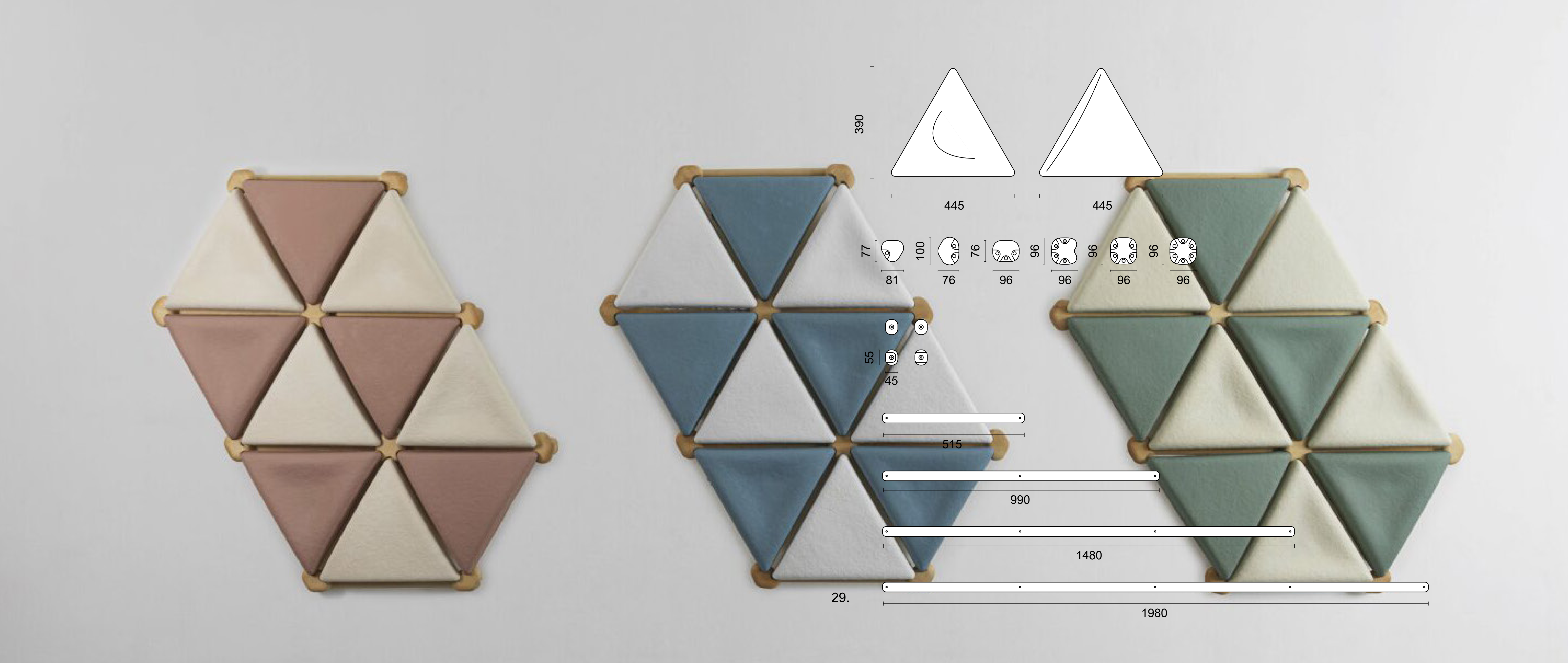

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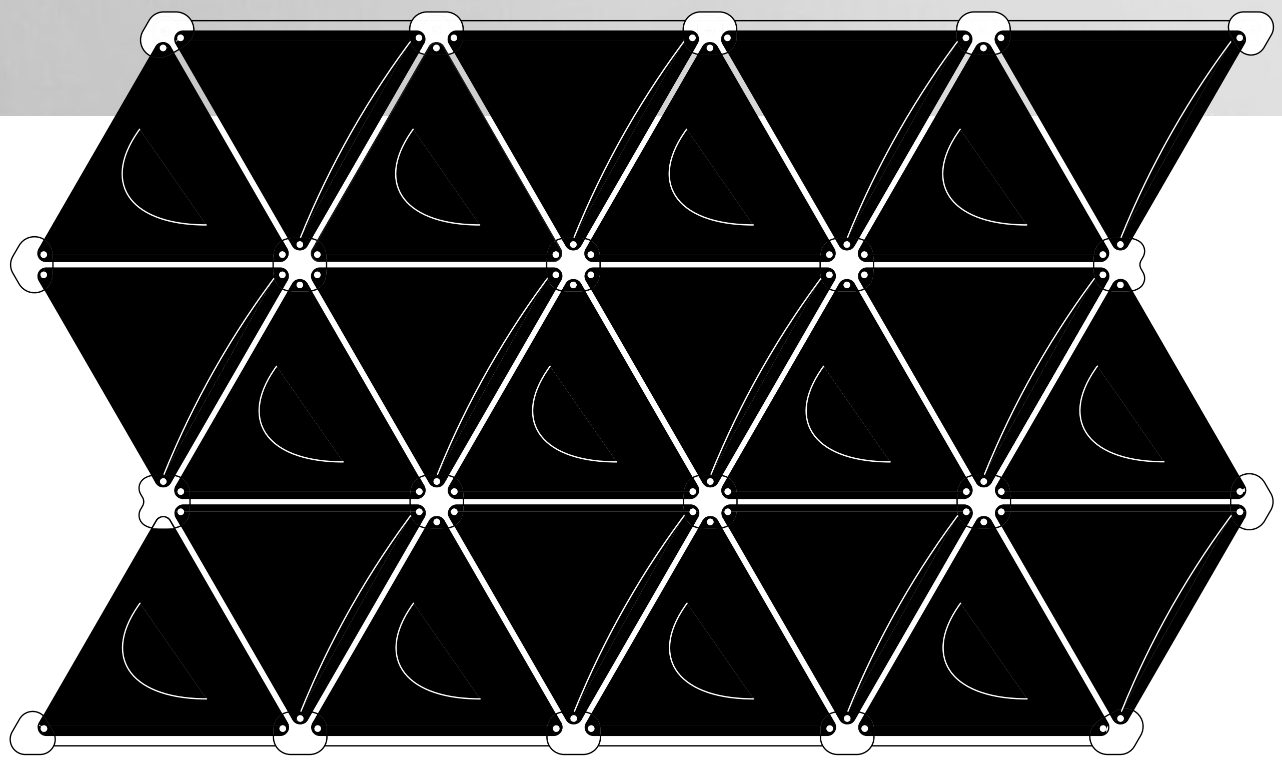

30.

Mogu Foresta System

The Foresta system, developed in collaboration with Arup, takes the innovation a step further by showcasing a modular acoustic panel system made from mycelium and upcycled textile residues. The system features a visually striking design inspired by the shapes of natural wood branches and the adaptability of modular structures and enables easier installation and maintenance.

It has been implemented in various commercial interiors and has won awards for its sustainable design, including the German Design Award in 2022

Figure 28. *Mogu Foresta system:* interchangeable acoustic paneling system installed showcasing colours and configurations

Figure 29. *Components of Mogu Foresta System:* Drawing adapted by author from Mogu resources, 2024

Figure 30. *Arrangement elevation Mogu Foresta System:* Drawing adapted by author from Mogu resources, 2024

3.2. **Technical analysis and alternative identification**

The aim of this section is to identify, based on the collection and comparison of data regarding material properties, to which conventional building materials each type of microbial material is best suited as an alternative.

The study also aims to assess how viable and competitive biocement and mycelium composite materials can be in an existing market in terms of their mechanical, thermal and acoustic properties.

3.2.1. **Production processes**

Understanding the production processes can aid in better understanding of the materials and how they work. This is critical to building a base for analysis to follow. On top of this, the production process of mycelium composites and biocement can be understood as emergent from human intervention into the self-assembling hierarchical biological structures of the microorganisms themselves (Vélez, 2023). Therefore, the production process can be looked at not from the perspective of the steps and requirements but rather expanded to exploring how human processes influence the behavior of the microbial self-assembling processes and vice versa[20,21]. In this exploration of production processes and conditions, I will gather information of how these materials are being produced from a technical perspective, the human approach, and translate these to explore how these processes can be viewed with the agency of the microorganism at the center. This aims to show how working with microorganisms to make materials is representative of a symbiotic relationship where we, as humans, tailor environments and conditions and ourselves to be optimal for the microbial metabolism, which in turn provides us with a material product.

[20] See figure 31: *Diagram of biocement production and the autonomy of microbial metabolism* - Page 133

[21] See figure 32: *Diagram of the mcelium composite production ecosystems and the autonomy of microbial metabolism* - Page 136

3.2.1.1. **Biocement**

The production of biocemented materials rests on the metabolism of microorganisms through a process of biomineralisation. The creation of concrete-like elements through biomineralisation is essentially a reversal of typical cement production whereby, rather than sourcing calcium-silicate hydrate from extracted limestone and clay while liberating CO_2, CO_2 can be sequestered through the metabolism of microorganisms with limestone as a product (GXN, 2023). Biomineralisation occurs naturally at both macro and micro scales, from large stony coral skeletons to microorganisms such as bacteria and microalgae. The process whereby microorganisms “grow” rock is known as Microbially-Induced Calcium Carbonate Precipitation or MICP. Biomineralisation through MICP is the backbone of most biocement production currently under development.

Biomineralisation through MICP

Microbially-Induced Calcium Carbonate Precipitation is a result of metabolic interactions between microbial communities and organic and inorganic compounds present in the environment whereby calcium carbonate is formed as a product (Castro-Alonso, et al., 2019). The metabolic processes of MICP that are utilised in the production of biocement through different methods consist mainly of urea hydrolysis and photosynthesis.

In the biocementation process, the calcium carbonate ($CaCO_3$), or limestone, produced through processes of MICP, acts as a cementitious binder to bind sand and aggregates to form concrete-like materials. In order to bind the material, the calcium carbonate crystals fill gaps between particles, binding them together with high strength and stable properties (Zhang, et al., 2023). Similarly, the production of calcium carbonate by bacteria opens opportunities for filling cracks of existing and new concrete structures to improve their durability. This is known as self-healing concrete, as cracks are filled autonomously when the bacteria is activated by exposure to air and water.

Production Processes

Each producer has a slightly different method of production, utilising different microorganisms with different properties and benefits.

The method utilised by BioMason uses non-modified bacteria to produce their patented, biologically generated calcium carbonate biocement (Stone Cycling), which is combined with locally-sourced aggregate. While this process is patented, the company does openly share in their product data sheet and publications that the BioLITH tiles are formed from the components of “biologics” i.e. the bacteria, aggregates and a solution containing sources of carbon (C), calcium ions (Ca^{2}+) and water. Also in their product data sheet, the company shares that the tiles are “formed by vibratory compaction in a semi-dry mix and cured in ambient temperatures, reaching full strength in less than three days” (Stone Cycling).

In a collaboration with GXN, a concrete column[22] form was also tested, where a bacterial solution, cementation solution and aggregate were added to formwork with reinforcements. The process takes about 3 days before the column is ready for use (GXN, 2023).

22

See case study: *Bioconcrete*
GXN, BioMason, Silas Inoue
Page 76-83

Prometheus Materials is exploring the use of cyanobacteria which have the capacity to photosynthesise. This utilises a different mechanism of MICP, therefore, while the process is similar, the nutrients and conditions required will be different. The benefit of this method, although less developed, lies in the process of photosynthesis, whereby carbon can be sequestered and captured into useful materials. In this way, the production has the potential to be carbon negative.

23

See figure 31:
Diagram of biocement production and the autonomy of microbial metabolism - Page 133

Steps

Common procedure to produce a biocemented element is as follows[23]:

1. Select and prepare bacteria and nutrients
2. Preparing aggregate
    a. Cleaning
    b. Mixing
3. Add microorganisms, solution and nutrients to recycled aggregate
4. Pour/press and compact mixture into molds
    a. BioMason uses methods of vibratory compaction
5. Curing/binding - microbial self-assembling
    a. Microorganisms form calcium carbonate to bind aggregate
    b. At ambient temperatures
    c. This process can take up to 72 hours (maximum)
6. Post processing
    a. Remove formwork
    b. Clean and polish elements

Influential parameters

The following parameters influence the final product:
1. Strain selection: The unique characteristics of the metabolic process of each individual strain of bacteria or microalgae influence the resulting material properties.
2. Strain concentration: The concentration of an introduced bacterial strain is another key parameter affecting the product.
3.Nutrients: Selection and concentration of nutrients introduced into the concrete mixture directly influences the sise, morphology and distribution of calcite crystals within the concrete matrix.
4. Aggregate selection: The choice of aggregate impacts the material properties as well as aesthetics.
5. Supplementary materials: The introduction of further supplementary materials such as fly ash, when combined with microbial activity, can further enhance the properties of the material produced.

While the human labour goes home, and waits for the product to cure or bind, the microorganism takes over the production process. Nobody needs to explicitly tell the bacteria to bind, or even fill cracks, but rather the bacteria respond to the environmental conditions and performs the process autonomously, and somewhat independently from human instruction or control.

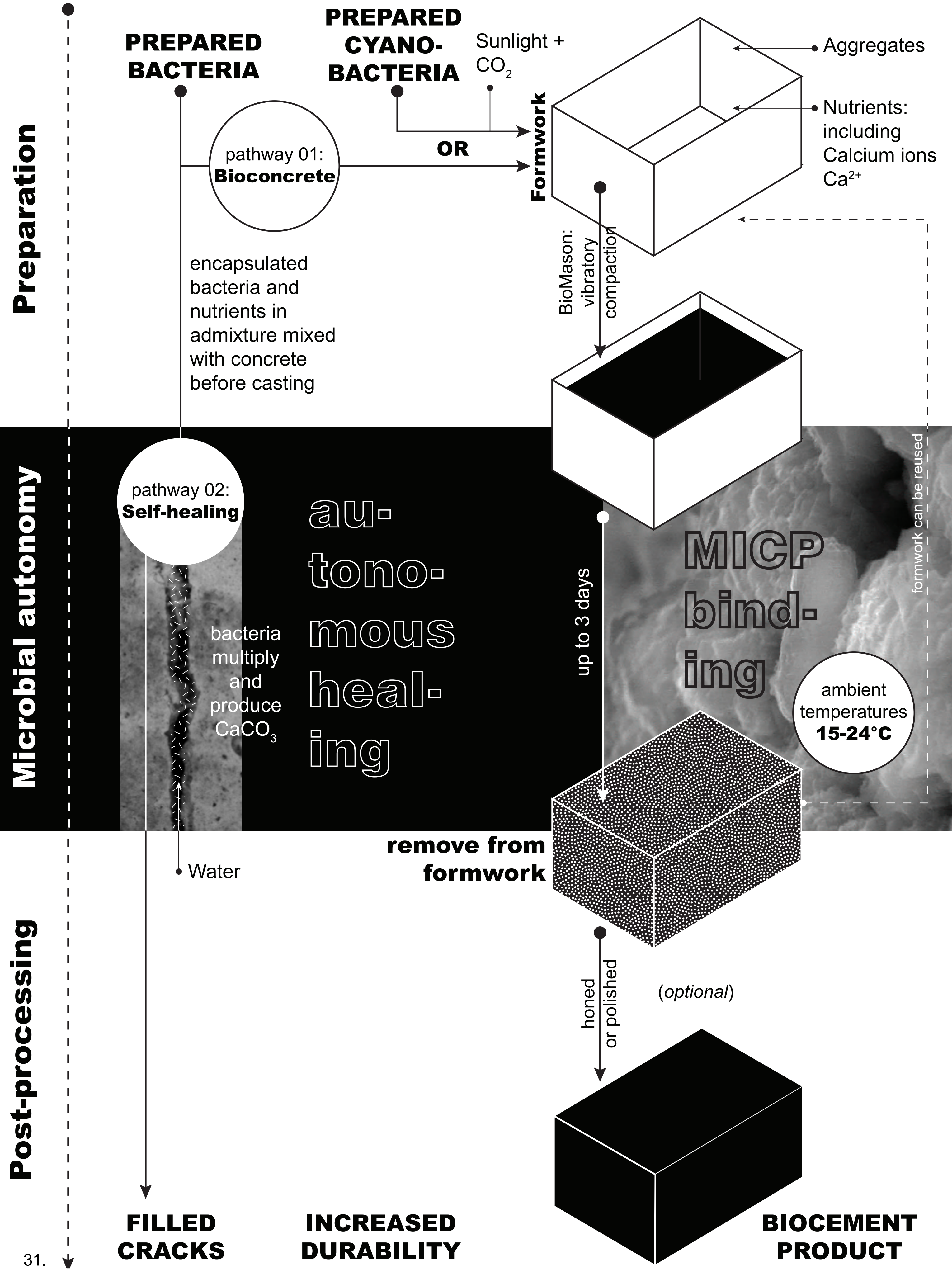

Figure 31. *Diagram of biocement production and the autonomy of microbial metabolism:* Diagram by author, 2024

3.2.1.2. **Mycelium Composites**

The process of mycelium composite production is fairly easily reproducible, and information is easily accessible as to steps, processes and conditions required to successfully grow mycelium composite materials[24]. The process can be easily broken down into steps, which opens the opportunity to adapt and better design material ecosystems to work more collaboratively with what fungi have to offer.

Steps

The common procedure to produce a mycelium composite element is as follows:

1. Substrate preparation
    a. Selection
    b. Preparation
    c. Sterilisation: Processes for substrate sterilisation and disinfection include one or a combination of the following: steam, heat pressure, hydrogen peroxide, acid sterilisation, basic sterilisation, UV/E- beam, boiling, pasteurisation or disinfection with oil emulsions (Vélez, 2023, p. 20)
    d. Additives: plasticising agents can be added to the growth medium to enhance the mechanical properties of the final material (Vélez, 2023, p. 20)

2. Strain selection and preparation

3. Fermentation – fungal self-assembling
There are multiple processes for different material outcomes. The most common, primarily developed by Ecovative Design, along with other researchers and developers, involves a simple process of inoculation of spores or colonised particles which are mixed with a substrate in a mold, which is removed after an incubation period to reveal the final mycelium composite product (Vélez, 2023, p. 21).
    a. Inoculation: Introducing spores, mycelia or colonised particulate substrate into substrate (Vélez, 2023, p. 22)
    b. Homogenisation (optional): mixing or blending to achieve homogeneous distribution of microorganisms
    c. Incubation: Incubation is where the biochemical transformation of the substrate happens, and the fungal biomass is created (Vélez, 2023, p. 22). Specific conditions are necessary to promote fungal growth including light, relative humidity, CO_2 concentration, temperature and time.
        i. Light: Darkness
        ii. Relative Humidity (air): 80-100% (min 20%,40%)
        iii. CO_2 concentration: 1.500-5.000 ppm
        iv. Temperature: 24-30°C
        v. Time: 5-14 days (Vélez, 2023, p. 101)
    d. Extraction: optional at this stage

4.Post processing:
    a. Inactivation (also known in industry as curing): Stopping the growth of the fungus (and modulating organisms) so that it remains incapable of transforming any matter that comes into further contact with it (Vélez, 2023, p. 24).
        ii. Drying: It is important that at the end of the drying step that the moisture of the material is less than 30%, but ideally under 8% (Vélez, 2023, p. 24). Drying temperatures generally range from around 50°C to 180°C (Sydor, Cofta, Doczekalska, & Bonenberg, 2022)

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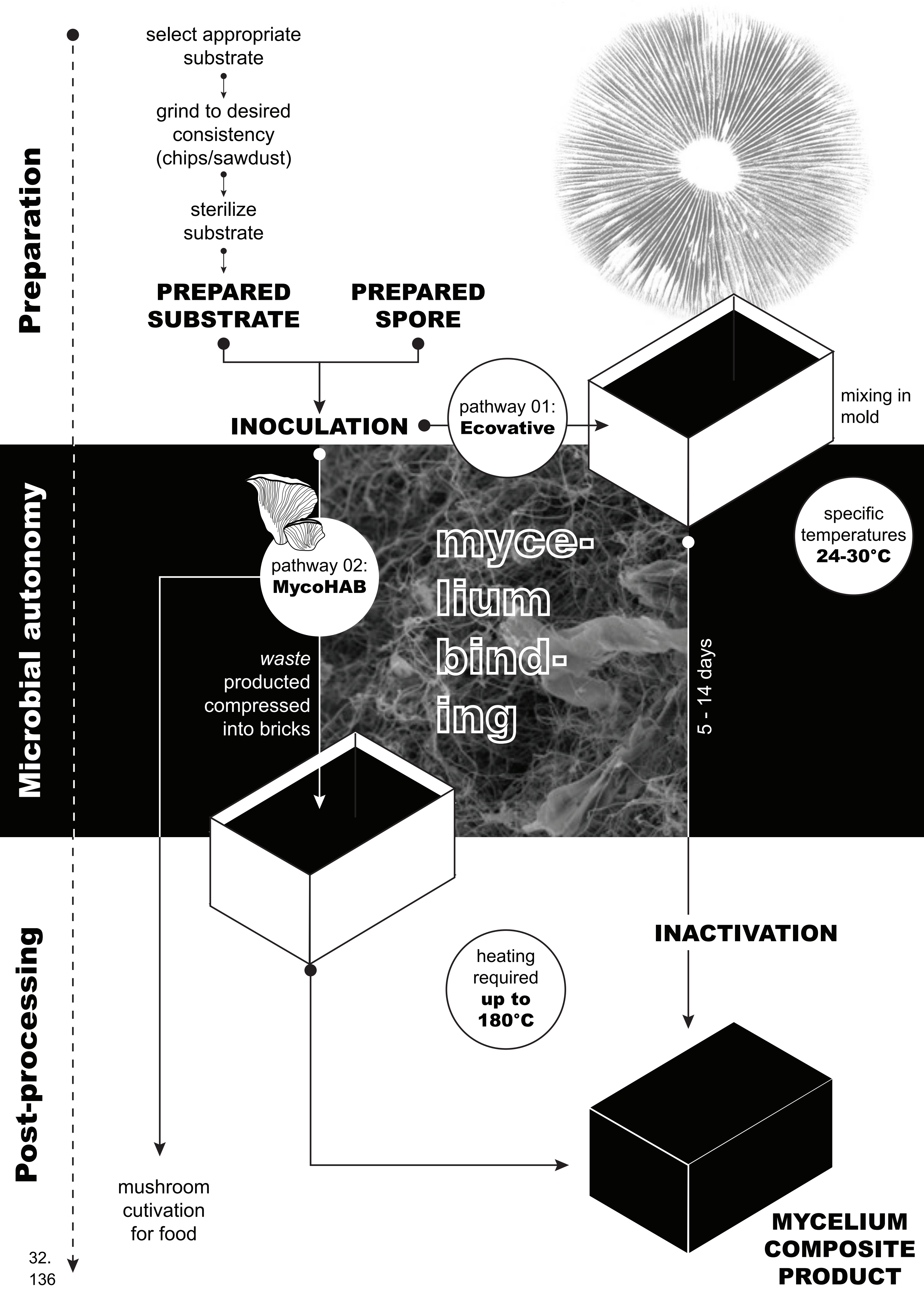
[24] See figure 32:
Diagram of the mcelium composite production ecosystems and the autonomy of microbial metabolism - Page 136



Based on these steps and conditions, it is possible to design further material ecosystems to further improve not only the material properties, but also regenerative properties, both environmental and social. The MycoHAB project in Namibia embodies this, working with mycelium to provide both food and housing for struggling communities, while utilising overpopulated vegetation as substrate. Both of these processes are governed by the metabolism of the microorganism, taking over the food and material production process in response to chaning environments.

Figure 32. *Diagram of the mycelium composite production ecosystem and the autonomy of microbial metabolism*: Diagram by author, 2024

3.2.2. **Material properties and uses**

In order to assess the viability of biocement based and mycelium composite materials as alternatives to existing market materials, I will collect and compare data regarding the material properties in relation to mainstream materials intended for specific purposes. In order to assess the technical viability and possible applications of microbial materials, this study will cover the physical, mechanical and thermal properties of the existing microbial products identified in the previous section as well as some of the most common construction materials including concrete (ready-mix, tiles and masonry units), clay bricks and thermal insulation (glass wool and explained polystyrene (EPS)).

The properties to be explored and discussed are as follows:
3.1.2.1 Physical properties:
    Density
    Water Absorption
3.1.2.2 Mechanical properties:
    Compressive strength
    Tensile strength
    Flexural strength
    Modulus of Elasticity
3.1.2.3 Thermal and acoustic properties:
    Thermal conductivity
    Acoustic performance: Noise reduction coefficient/ sound reduction index
    Fire resistance

Through this analysis and comparison, the aim is to identify the current and potential uses of materials based on microbial metabolism as alternatives to conventional building materials, and to outline the basis for the environmental analysis and comparison to follow.

3.2.2.1 **Physical Properties**

The physical properties of a material influence other properties that are relevant to the viability of materials for specific uses. Table 01[25] and the discussion showcase and analyse data collected on the relevant products as mentioned above in relation to physical properties of density and water absorption

High-density materials

Concrete can have a range of densities depending on its intended use and composition . Ordinary CEM I ready-mixed concrete for structural applications usually has a higher density, around 2380 kg/m^3 (Mineral Products Association (MPA) UK, 2024). By increasing porosity, with additives or otherwise, or changing aggregate, the density of concrete can be decreased, making it lighter and easier to transport and support, as well as less thermally conductive. However, decreasing density can negatively impact mechanical properties, therefore the intended use should inform the chosen concrete type. Concrete masonry units are also produced at different densities; lightweight, medium weight and heavy weight as outlined in table 01.

Clay bricks have a medium weight density at around 1640 kgm^3 (Wienerberger, 2020) . This and their smaller dimensions can make them easier to transport and construct with.

Basilisk Repair Mortar MR3, being composed of similar elements to regular concrete including Portland cement, has the highest density of the biocement materials. According to ASTM standards it would still be considered medium density concrete. However, basilisk also produces a healing agent (HA) admixture which can be added to any concrete composition to attribute autonomous-healing properties, meaning that concrete containing Basilisk healing agent (HA) can have a wide range of densities.

[25] See table 01: *Physical properties of biocement and mycelium composite materials in comparison to conventional building materials* - Page 140

Table 01: *Physical properties of biocement and mycelium composite materials in comparison to conventional building materials*

		Physical Properties	
		Density (kg/m^3)	**Water absorption**
Biocement	**Basilisk Repair Mortar MR3**	1862 (7days) 1867(28 days)	-
	BioMason BioLITH tile	1800 (Stone Cycling), 2144 *	<10% (Stone Cycling), 8% *
	Prometheus Materials ProZero Masonry Unit	85% of Portland cement CMU	ASTM C129 and ASTM C90 certified **
Mycelium Composites	**MycoHab Blocks**	-	-
	Ecovative Design MycoComposite 027	115-128 (Ecovative Design, n.d.)	-
	Ecovative Design MycoComposite 584 Panels	140 (Ecovative Design)	-
	Ecovative Design MycoComposite 570 Panels	190 (Ecovative Design)	-
	Mogu Acoustics	100 (Mogu , 2024)	-
	Mogu Foresta System	100 (Mogu)	-
Control: Ready-Mixed CEM I	**Ready-mixed concrete C28/35 CEM I (Sector)**	2380 (Mineral Products Association (MPA) UK, 2024)	-
Standards: CMU	**EN Standards (Europe)**		<6% (for external use), up to 15% (internal) - EN 771-3
	ASTM Standards (USA)	Lightweight: <1680, Medium weight: 1680-2000, Normal weight: >2000 (ASTM C90)	<12% (ASTM C90)
Control: Clay Brick	**Wienerberger Oast Russet Sovereign Stock**	1640 (Wienerberger, 2020)	<21 % (Wienerberger, 2020)
Standards : EPS	**EN Standards (Europe)**	15-30 (EN13163)	<5% (EN13163)
	ASTM Standards (USA)	14.4-32 (ASTM C578)	<4% (ASTM C578)

*(Biomason Denmark, 2022) , **(Concrete Products, 2023)

BioMason's BioLITH tile has a density of 1800 kg/m³ (Stone Cycling) to 2144 kg/m³ (Biomason Denmark, 2022), classifying it in the medium to heavy weight category according to the ASTM C90 standard which is also more dense than clay bricks. It is also reported that their column, in conjunction with GXN, is 20% lighter than conventional concrete, however it is not confirmed as to with which type of concrete and aggregates the comparison was made.

Prometheus Material's has not released a precise density for their product, but they claim that their Bio-Block Masonry Unit Solution is 85% the weight of a standard Portland cement concrete masonry unit (CMU). Considering a CMU of a density of 2000 kg/m³, then Prometheus Material's solution could be assumed to have a density of 1700 kg/m³, classifying it at the lower range of the medium weight category, and lighter than an ordinary concrete alternative.

While a higher density is generally related to improved strength and durability, however a lighter material is easier to support and transport. Biocement offers a good relationship between the two, offering relatively lower density similar of that to light and medium weight concrete units, while still providing comparable strength (see section 3.1.2.2. Mechanical properties).

Similarly, a higher water absorption can lead to increased vulnerability to cracking failure, freeze-thaw damage, and corrosion of reinforcement and therefore lower durability. BioMason's BioLITH tile is compliant for internal use according to EN 771-3 at a water absorption of <10%, while going beyond an average of <12% for ASTM standards. Suppliers propose the product to be used for both indoor and outdoor applications as their intended use is non-structural. There is no specific data for Prometheus Material's product, yet it has been confirmed that their bio-concrete masonry units are ASTM C129 and ASTM C90 compliant.

Low-density materials

Standard EPS insulation is incredibly lightweight, which contributes to its low thermal conductivity. On the other hand, such lightweight materials have lower mechanical properties and therefore are more suitable for non-structural purposes.

Mycelium composite materials such as Ecovative Design’s MycoComposites and Mogu’s acoustic panels also have a much lower density than concrete, clay brick and biocement materials, however they are higher in density than standard EPS insulation. This could make them more suitable for application where they need to have a higher structural integrity. Mycelium composites can also be compressed to increase their density as showcased in MycoHAB’s process, however no exact data on this effect could be accessed.

The following sections will explore how these factors effect the material’s performance in terms of mechanical, thermal and acoustic properties.

3.2.2.2. **Mechanical Properties**

The mechanical properties of a material play the largest role in determining a material’s viability for structural application. Table 02[26] and the discussion analyse data collected on the relevant products as outlined above in relation to the mechanical properties of compressive strength, tensile strength, flexural strength and modulus of elasticity

[26] *See table 02: Mechanical properties of biocement and mycelium composite materials in comparison to conventional building materials* - Page 144-145

Strength

For masonry construction, a high compressive strength is one of the primary factors that contributes to the success of a material. Concrete for structural purposes should typically have a compressive strength of 3.5 MPa for non-load-bearing and 7.5-15 MPa for load-bearing construction, sometimes ranging up to 22.5 MPa for critical purposes according to EN 771-3. Similarly, the ASTM standard C90 for load bearing structures requires a minimum of 13.1 MPa and ASTM C129 a minimum of 4.1 MPa for non-load-bearing structures. Fired clay bricks also have a high compressive strength exceeding 21 MPa, making them an effective component for structural masonry construction.

All of the products in the biocement category should fulfil these requirements for both load-bearing and non-load-bearing construction based on ASTM and EN standards. Mycelium composites generally have a lower compressive strength, however MycoHAB’s MycoBlock can reach strengths of up to 26 MPa, making it suitable too for structural purposes.

Of the biocement products, Basilisk Repair Mortar MR3 boasts the highest compressive strength after 28 days of 36.7 MPa, however the product is promoted as a repair mortar with a layer thickness of maximum 40 mm (Basilisk) rather than for full scale casting. This may propose some limitations for the comparability

Table 02: *Mechanical properties of biocement and mycelium composite materials in comparison to conventional building materials*

		Mechanical Properties			
		Compressive strength (MPa)	**Tensile strength (MPa)**	**Flexural strength (MPa)**	**Elasticity Modulus (GPa)**
Biocement	**Basilisk Repair Mortar MR3**	17.6 (7days) 36.7 (28 days)	-	6.0 (7days) 7.0 (28 days)	11.9
	BioMason BioLITH tile	30.0	>1.0	7 (Biomason Denmark, 2022)	-
	Prometheus Materials ProZero Masonry Unit Solution	16.54-24.1 (Prometheus Materials, n.d.)	-	4.5- 6.8 (Prometheus Materials, n.d.)	-
Mycelium Composite	**MycoHab Mycelium Composite Blocks**	8.0-26.0 (United States Patent No. 17/648,105, 2022)	-	2.9 (flexural strength) (United States Patent No. 17/648,105, 2022)	-
	Ecovative MycoComposite 027	0.07-0.15 (Ecovative Design)	0.020-0.028 (Ecovative Design)	0.100-0.23 (Ecovative Design)	-
	Ecovative MycoComposite 584 Panels	0.015-0.028 (Ecovative Design)	0.028-0.040 (Ecovative Design)	0.079-0.110 (Ecovative Design)	-
	Ecovative MycoComposite 570 Panels	0.2-0.4 (Ecovative Design)	0.04-0.14 (Ecovative Design)	0.12-0.21 (Ecovative Design)	-
	Mogu Acoustics	0.011 (Mogu)	-	0.05 (Mogu)	-
Control: concrete block	**EN Standards (Europe)**	3.5 (non-load-bearing), 7.5-22.5 (load-bearing) – EN 771-3, EN 772-1	0.7-2.5 (approx. 10% of compressive strength) - EN 12390-6	0.7-2.5 - EN 1339	20-35 - EN 12390-13
	ASTM Standards (USA)	4.100 (non-load-bearing - ASTM C129) 13.1 (load-bearing - ASTM C90),	-	-	-
Control: Clay Brick	**Wienerberger Oast Russet Sovereign Stock**	>21 (Wienerberger, 2020)	-	-	-
Control: EPS Insulation	**EN Standards (Europe)**	0.070-0.250 (EN13163)	-	-	-
	ASTM Standards (USA)	0.069-0.172 (ASTM C578)	-	-	-

of this product with others in block format. As this product is also composed of primarily portland cement, limestone powder and fly ash with the addition of bio-based enzymatic catalyst designed to activate and heal cracks (Basilisk), it is also unfair to compare it as if it were in the same category as products cemented entirely using microorganisms in terms of compressive strength. The advantages of the metabolism of the microorganism are more relevantly discussed in terms of durability and product life time as well as in an environmental comparison. However, it is useful to note that the addition of bacteria to the concrete matrix does not discount the mechanical integrity of the material.

BioMason's BioLITH tile also claims a high compressive strength of 30 MPa, even though the product is marketed for tiling rather than structural purposes. This may have to do with the dimensions of the product, yet BioMason does not market any other products of different forms in their range. The company has collaborated with the Danish firm GXN to grow a column that achieves a compressive strength of 30 MPa. Through this research they claim that the BioMason column is three times stronger than cement, and therefore requires less material to achieve the same strength (GXN, 2023). This project showcases the potential of this material yet to be scaled up in a commercial setting.

Prometheus Materials, on the other hand, includes a block masonry unit solution in their range which has recently been proven to meet the ASTM standards for both load-bearing and non-load-bearing construction with a compressive strength of 22.1 MPa. While Prometheus Material's products have a compressive strength on the upper end of EN requirements, they are slightly lower than BioMason's reported 30 MPa. Prometheus Materials is working on developing a wider range of units including acoustic panels, block-based construction units, paving solutions, and even developing a ready-mix solution for broadening their applications.

The tensile strength is often excluded from data sheets of biocement, concrete and brick products as it is not a primary characteristic of block masonry unit construction. Similarly, flexural strength is not a primary characteristic of block units. However, the flexural strength of biocemented materials is noted on product data sheets and company websites to be marginally higher than conventional concrete according to EN standards, yet it is still relatively low compared to other building materials implying the need for reinforcement for larger units.

Of the mycelium composite materials, MycoHAB's MycoBlocks showcase the highest compressive strength at 8-26 MPa, which is also above the standard for both concrete masonry blocks and clay bricks, making them a highly suitable material for structural masonry construction methods.

Other mycelium composite materials including Ecovative Design's MycoComposites and Mogu's acoustic panels have a much lower compressive strength, at less than 1 MPa, and are therefore not suitable for structural applications. Their compressive strength is more comparable with EPS insulation, where strength is not the intended purpose of the product. It is possible to make mycelium composites with slightly higher compressive strengths by substituting substrates, as showcased in Ecovative Design's MycoComposite 570 panels or compressing the mycelium as showcased by MycoHAB.

Biocement and mycelium composite materials exhibit mechanical strength properties comparable to standard construction and compliant with ASTM and EN standards depending on the intended application. BioMason, Prometheus Materials, Basilisk and MycoHAB all produce products which are suitable for block unit construction purposes for both load-bearing and non-load-bearing walls based on their mechanical properties. There is however limited data on other unit dimensions and precast elements, making a comparison to the versatility of concrete limited in this regard. Ecovative Design and Mogu's products are not suitable for structural applications and are suited rather for non-structural applications.

Durability

As the materials in discussion are relatively new, their durability is still to stand the test of time in a real-world context.

Basilisk offers immediate solutions to durability with their products containing bacteria that enable self-healing properties. Cracking in concrete is one of the biggest problems for durability as it means that water can penetrate the concrete and cause corrosion to steel reinforcement elements. By using the autonomy of bacteria, Basilisk has developed a range of products which use water and oxygen penetration caused by crack formation to their advantage to activate the metabolism of the bacteria and initiates the formation of calcium carbonate which seals the crack so that the concrete remains waterproof. This autonomous healing promises improved durability with minimal human intervention and maintenance requirements. It has been noted in some research papers (Jin et al.,2017, Luo et al., 2018, Elsacker et al., 2021) that mycelium may offer an alternative to bacteria in self-healing mechanisms to improve the durability of concrete, however this line of research is underdeveloped.

On the other hand, mycelium composite materials are generally hygroscopic, and require external treatments to be made waterproof. These treatments can include painting, mud-lime rendering or covering with a roof to protect the elements. However, sometimes these treatments are not environmentally friendly and need to be considered in an environmental analysis. Mycelium composite materials have an estimated service life of around 30 years yet have the advantage of being inherently biodegradable. If conditions are suitable, mycelium composite materials will be able to last their intended life span then return naturally to the environment without leaving large amounts of waste in landfills.

3.2.2.3. **Thermal & acoustic properties**

Biocement and mycelium composite products also appear promising in terms of their thermal and acoustic properties. Table 03[27] and the discussion outline the thermal conductivity, noise reduction coefficient or sound reduction index (where applicable) and fire resistance of microbial materials along with conventional building materials.

While biocement is not commonly marketed as an insulating material, the products on the market under this category showcase more effective thermal insulating properties, where data is published by Prometheus Materials, than structural materials such as conventional concrete and clay bricks without compromising on strength. The ProZero unit allows for improved thermal insulation with a thermal conductivity of 0.0635 W/mK in comparison to the 0.7 W/mK of concrete and the 0.47 W/mK of clay bricks. The values achieved by Prometheus Materials also come close to the range of common thermal insulation materials such as rockwool and EPS but are not quite adequate to propose a suitable and competitive alternative in terms of thermal conductivity.

Similarly, Prometheus Materials has reported an improved noise reduction coefficient in comparison to conventional concrete. Their product is advertised to have a sound absorption noise coefficient ratio (NCR) of 0.60 compared to conventional concrete which has an NCR of 0.05.

Mycelium composite materials such as Ecovative Design's MycoComposite panels offer a more competitive alternative to standard insulation with their MycoComposite 584 showcasing a low thermal conductivity of only 0.047 W/mK, which is competitive with mainstream insulation such as rockwool and EPS while providing the environmental benefits associated with mycelium

[27] See table 03: *Thermal and acoustic properties of biocement and mycelium composite materials in comparison to conventional building materials* - Page 150-151

Table 03: *Thermal and acoustic properties of biocement and mycelium composite materials in comparison to conventional building materials*

		Thermal & Acoustic Properties			
		Thermal conductivity W/mK	**Noise reduction Coefficient - NRC**	**Sound Reduction Index - Rw (dB)**	**Fire resistance***
Biocement	**Basilisk Repair Mortar MR3**	-	-	-	Class A1
	BioMason BioLITH tile	-	-	-	Class A1 **
	ProZero Acoustic Panel Solution	0.0635 (Prometheus Materials, n.d.) /10%	0.60 (Watson, 2023)	-	-
	ProZero Bio-Block Masonry Unit Solution	0.0635 (Prometheus Materials, n.d.) /10%	0.60 (Watson, 2023) (Souza, 2023)	-	-
Mycelium Composite	**MycoHAB Blocks**	0.060 (United States Patent No. 17/648,105, 2022)	Attenuates sound (United States Patent No. 17/648,105, 2022)		Class 1 (United States Patent No. 17/648,105, 2022)
	Ecovative MycoComposite 027	0.042 (Ecovative Design)	0.6 (Ecovative Design)	-	Class A (Ecovative Design)
	Ecovative MycoComposite 584 Panels	0.0470 (Ecovative Design)	0.90 (Ecovative Design)	-	Pending
	Ecovative MycoComposite 570 Panels	0.061 (Ecovative Design)	0.40 (Ecovative Design)	-	-
	Mogu Acoustics	0.0450 (Mogu , 2024)	0.39-0.53 (Mogu , 2024)	-	Class B-D depending on finishing (Mogu , 2024)
	Mogu Foresta System	0.050 (Mogu)	0.33-0.39 (Mogu)	-	Class B (Mogu)
Control: CMU	**EN Standards (Europe)**	1.100-1.500 (normal weight), 0.35-0.7 (light weight) (EN 1745)	-	40-50 (EN 12354-1)	Class A1, REI 60 – REI 240 (EN 13501-1)
	ASTM Standards (USA)	0.700-1.300 (ASTM C518)	0.05-0.10	-	2-4 hours (ASTM E119)
Control: Clay Brick	**Weinerberger Oast Russet Sovereign Stock**	0.470 (Wienerberger, 2020)	-	-	Class A1 (Wienerberger, 2020)
Control: Glass Wool	**EN Standards (Europe)**	0.030-0.040 (EN 12162)	0.70–1.00 (EN ISO 11654)	45-50 (EN ISO 11654)	Class A1 or A2 (EN 13501-1)
	ASTM Standards (USA)	0.030-0.045 (ASTM C518, ASTM C177)	0.70-1.00 (ASTM C423)	-	Flame spread index 0-25, smoke development index 0-50 (ASTM E84)
Control: EPS	**EN Standards (Europe)**	0.030-0.040 (EN1 12163)	0.10-0.20 (EN ISO 11654)	-	Class E, fire-retardant EPS - Class (EN 13501-1)
	ASTM Standards (USA)	0.030-0.036 (ASTM C518, ASTM C177)	0.10.0.20 (ASTM C423)	-	Flame spread index 20-25, smoke development index 400-450 (ASTM E84)

*Class A1: Non-Combustible, Class B: Combustible – Very Limited, Class D: Combustible – Medium, Class E: Combustible – High contribution

** (United States Patent No. 17/648,105, 2022) materials. MycoHAB's MycoBlock manages to combine both high strength suitable for structural applications with a relatively low thermal conductivity of 0.06 W/mK which has the potential to reduce material consumption in general with one material providing a double purpose.

The MycoComposite materials, particularly the 584, also have the added benefit of high performing acoustic properties with an NCR of 0.9, on par with the standards for rockwool insulation and exceeding that of EPS. Due to these properties of mycelium composites, companies such as Mogu have developed specific products for acoustic purposes, with their acoustic range reaching an NCR of up to 0.53 for specific shapes such as the kite and wave. Mycelium composite materials such as these offer a great alternative to insulation materials, particularly EPS, for both thermal and acoustic properties.

In terms of fire resistance, biocement products are non-combustible, complying with the highest fire resistance class ratings, comparable with that of regular concrete. Mycelium composites on the other hand require further treatments to be more resistant to fire, however MycoHAB claims that their product has "fire resistant properties" (United States Patent No. 17/648,105, 2022) although they are not specified. This may be one drawback of the mycelium composite material for the application of insulation, as fire resistant insulations such as rockwool have become more popular with new EU regulations for fire resistance performance in comparison to the cheaper competitor EPS with low fire-resistant properties (IAL Consultants, 2023).

3.2.3. **Discussion - Determining alternatives**

Biocement and mycelium composite materials can offer viable alternatives to existing construction materials based on their physical, mechanical, thermal and acoustic performance.

For structural purposes, compressive strength is the prominent factor to consider when comparing to standard materials such as concrete and clay bricks. Both BioMason and Prometheus Material's products exceed standard values for load bearing concrete and clay masonry, making them suitable for structural application. Prometheus Materials currently produces a masonry unit, comparable with both concrete and clay brick for structural masonry application. Similarly, the compressive performance of biocement implies potential application for larger cast elements such as columns. This has already been tested at a small scale by BioMason in collaboration with GXN, providing further substantiation that biocement has potential to be an alternative to concrete beyond tiles and masonry units, which is where market production is currently limited. Factors such as research, testing and cost may affect scaling up in this sector.

As Basilisk healing agent (HA) additive enhances properties of existing concrete, its applications differ from the other biocement materials studied. Basilisk rather serves to improve durability extend the service life of ordinary concrete. The composition of Basilisk's repair mortar (MR3) boasts high compressive strength after curing, making it suitable for a wide range of building types. It is most commonly used in the industrial and infrastructure sector, where the autonomous healing capability and improved waterproofing make it especially beneficial.

MycoHAB's MycoBlocks showcase the highest compressive strength of the mycelium composite materials due to the added step of compressing bricks after fermentation and before firing. The compressive strength of MycoBlocks produced in this method is comparable with standard values for both concrete and clay masonry. Due to the production method, it may however be harder to create larger elements such as columns from this material. This is something that would require further research to prove its viability. Therefore, for the purpose of this comparison, MycoBlocks are comparable in the category of masonry unit construction.

On top of the structural potential, the structural microbial materials produced by Prometheus Materials and MycoHAB also showcase a relatively low thermal conductivity in comparison to concrete and clay bricks. This could help reduce operational energy and carbon throughout a building's use.

There are however mycelium composite compositions, such as those developed by Ecovative Design and Mogu, that showcase even lower thermal conductivity and would be more suitable as alternatives to the most commonly used insulation materials: glass wool and EPS. Ecovative Design's MycoComposites 027 and 584, as well as Mogu's acoustic panels are within the range of glass wool in terms of thermal conductivity. While they are slightly higher than standard EPS, some compositions have the added benefit of being more resistant to fire, particularly Ecovative Design's MycoComposite 027 which was rated class A for fire resistance. Both biocement and mycelium composite materials also perform well in noise reduction, rating in general higher than all of the conventional materials considered aside from glass wool.

While microbial materials present great opportunities for shifting material practices in the construction industry in a more collaborative and sustainable direction, there are practical limitations in scalability that need to be addressed.

The comparison matrix below (table 04) will serve as a basis for the following environmental comparison with the aim to see how novel microbial materials compare with existing alternatives in terms of their environmental impact covering resource depletion, end of life scenarios, energy requirements and carbon emissions.

		Microbial Materials					
		BioMason BioLITH Tile	**Prometheus Materials Masonry Unit**	**Basilisk self-healing mortar**	**MycoHAB Mycoblock**	**Ecovative Design panels**	**Mogu Acoustic panels**
Standard Industry materials	**Ready-Mix CEM I concrete**	x	x	x			
	CEM I Concrete Masonry Unit (CMU)		x		x		
	CEM I Concrete Tile	x	x				
	Standard Clay Brick	x	x		x		
	EPS Insulation				x	x	x
	Rockwool Insulation				x	x	x

Table 04: *Comparison matrix of biocement and mycelium composite products as alternatives to conventional building materials*

3.3. **Environmental analysis & comparison**

To assess, and be able to compare, the environmental impact of biocement and mycelium composites in comparison to ordinary concrete and insulation materials I will explore the following categories of environmental impact through a whole life-cycle approach:

3.2.1 Resource depletion –
Assessing and comparing the resources required, their availability, renewability and the potential for remediating waste streams through a circular approach.

3.2.2 End-of-Life –
Assessing and comparing the recyclability, biodegradability or waste at the end of the material life.

3.2.3 Energy consumption & Carbon footprint (carbon emissions and sequestration potential) –
Assessing and comparing the total embodied energy and embodied carbon of the material throughout the life cycle

Scope & Boundaries

Throughout the following analysis, I will attempt to encompass and discuss through a cradle-to-cradle approach considering production, construction, use and end of life stages as well as looking beyond the system boundaries to reuse, recovery and recycling potential.

Table 05 represents the life cycle phases that are represented throughout the different topics to be discussed in the following sections:

Life-cycle phases represented																	
	A			A.1		B							C				D
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water	De-construction	Transport	Waste Processing	Disposal	Reuse-Recovery-Recycling potential
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
3.2.1	■																
3.2.2	■	■	■	■			■	■	■		■						
3.2.3															■	■	■

Table 05: *The life-cycle modules represented through the topics of the environmental analysis*

Table legend:
A - Production Stage
A.1 – Construction Process stage
B – Use stage
C – End of life stage
D – Resource recovery stage

3.3.1. **Resource depletion**

The earth only has a finite source of resources, and current rates of extraction are placing demand higher than what can be naturally renewed. The heavy extraction of resources also has an impact on the healthy functioning of ecosystems, which as noted in previous analyses, is supported by and supports the vitality of a diverse range of species.

In this section, the impact of biofabricated and conventional materials in terms of resource depletion will be explored and compared. This will involve identifying the resources required for the production of concrete, clay bricks, standard glasswool and EPS insulation along with biocement and mycelium composites and assessing their renewability and the environmental impact of their extraction. Following this, material alternatives will be compared in relation to their approach to resource requirements and acquisition, identifying the different and common resources required, their demand and alternative resource approaches.

3.3.1.1. **Standard practice**

Concrete & Ordinary Portland Cement

The production of concrete and its component ordinary portland cement (OPC)[28] relies on a few crucial resources that are non-renewable including:

1. Limestone

Limestone, or calcium carbonate, is a sedimentary rock that is the primary raw material for the production of OPC. Due to the high demand of the concrete and cement industry, limestone is mined at an unsustainable rate. While not only depleting a non-renewable resource, the extraction of limestone also has a lasting impact on the landscape from which it is extracted which results in habitat disruption for many other species. Efforts are being made within current industrial practices to partially replace limestone with supplementary cementitious materials, which are usually waste streams from other industries. While this does help reduce the need for limestone extraction, there is much more to be done in this regard.

2. Clay

Although clay is required in lower quantities than limestone, it is required for the clinkerisation process, and due to the scale of the cement industry is heavily mined for cement manufacturing. Clay is generally considered a non-renewable resource as is not replenished on a human timescale.

3. Gypsum

A naturally occurring mineral which is added during the final grinding stage of OPC to control the setting time.

4. Aggregates

Traditional aggregates including sand, gravel and crushed stone are natural occurring non-renewable resources which are mined

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[28] See table 06: *Comparison of cementitious materials approach to resources including bio-fabricated and extracted processes*- Page 166

in large quantities to support the high demands of the concrete industry. The extraction of these resources is an unsustainable process in terms of resource depletion and habitat disturbance.

5. Fossil Fuels

The production of OPC is an energy intensive process mainly due to the high heat required for kilns. Currently a large portion of the energy supply comes from the burning of fossil fuels, which contributes largely to resource depletion and carbon dioxide emissions.

The production of concrete also requires water, which while it may technically be considered a renewable resource, is becoming more and more scarce due to the growing population and climate change. Growing population and industry are placing increasing demands on the resource. Along with this, the world's water supply is also critically affected by natural systems critically affected by climate change, which is manifesting in unpredictable rainfall patterns, melting ice caps, rising sea levels, flooding and drought, meaning that water supply is increasingly unpredictable. It is reported that roughly half of world's population experiences water scarcity at some point during the year (IPCC, 2022), therefore water is a critical resource to preserve now and for the future as populations are predicted to grow, and global temperatures predicted to increase if business continues as usual.
Concrete is the second most used material after water, and with this high demand, the production of OPC concrete consumes 8-9% of water globally per year (Prometheus Materials). Careful consideration needs to be given to reducing the impact of the concrete and cement industry on water scarcity.

The production of clay bricks involves the use of resources throughout the stages of raw material extraction, manufacturing, and firing:

1. Clay

The primary raw material for making bricks, composed mainly of varying quantities of aluminum oxide, silicon oxide and iron(III) oxide (Bauen mit Backstein Zweischalige Wand Marketing e. V., 2016), clay, is a naturally occurring sedimentary material extracted from quarries. Clay is a non-renewable resource as it takes a long time to form, and due to unsustainable mining practices and environmental degradation, high quality clay is becoming increasingly scarce.

2. Sand

Sand is necessary to stabilise the mineralogical composition of the raw clay and improve material properties. Sand is also a non-renewable resource which is becoming increasingly scarce, and its extraction can cause environmental issues such as habitat disruption.

3. Mineral oxides

Mineral oxides, such as manganese oxide or iron oxide, are added to achieve certain colours. Mineral oxides are finite resources which are mined as minerals or derived from industrial by-products.

4. Water

Water is required during the mixing and forming stages of brick production. In most regions, water is considered renewable, but, as mentioned before, its overuse in certain contexts can place strain on water sources.

5. Fossil Fuels

A significant amount of energy is required to run the kilns for the firing process, where bricks are fired at high temperatures, around 900 - 1250°C, to achieve their desired strength and durability. The firing process is energy-intensive and contributes to significant CO_2 emissions and air pollution if energy is derived from fossil fuels.
It is necessary to consider renewable energy forms to reduce the

environmental impact of the clay brick manufacturing process.

The energy demands for clay brick firing contribute substantially towards the environmental impact of clay bricks. The upstream chains associated with clay and manganese oxide depletion also result in eutrophication (Bauen mit Backstein Zweischalige Wand Marketing e. V., 2016) along with other environmental impacts including habitat destruction.

Insulation

Currently, the most popular insulation materials in the EU, glasswool and EPS (IAL Consultants, 2023), are produced using a large portion of non-renewable resources.

Glass wool

Glasswool (or fiberglass) insulation requires the following resources:

1. Sand
The primary raw material for glass wool is silica sand, a non-renewable resource which requires extraction, which can have impacts on land, ecosystems and habitats. Although it is considered an abundant material, it is finite and high-quality sources of silica sand are becoming increasingly scarce as demand is increasing.

2. Soda Ash
Used to reduce the melting temperature of glass, soda ash is sourced from non-renewable minerals including trona.

3. Limestone
Added to the glass batch to improve chemical resistance and durability, limestone, as discussed previously, is a non-renewable mineral resource.

4. Fossil Fuels
The production of glass wool requires significant energy to melt the raw materials at very high temperatures. This energy is typically sourced from fossil fuels.

Glasswool can be made using up to 80% recycled glass (Isover, n.d.) to reduce demand for extraction of non-renewable resources such as silica sand. While this does improve the environmental impact of the product in terms of resource depletion, it is not possible to make glasswool insulation out of renewable resources entirely.

Expanded Polystyrene(EPS)

Expanded polystyrene (EPS) insulation[29] is a plastic-based material made from the polymerisation of styrene, a process which relies heavily on non-renewable resources:

1. Styrene
The primary raw material for EPS is styrene, which is derived from benzene, a non-renewable petroleum byproduct. The production of polystyrene heavily relies on fossil fuel extraction and refinement.

2. Expansion gas
Modern EPS uses pentane gas which is dissolved within the polystyrene bead (BPF, n.d.).

Both of these examples of insulation materials are dependent on non-resource extraction, and therefore it is important to turn to alternatives to move towards a more sustainable construction industry.

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[29] See table 07: *Comparison of insulative materials approach to resources including bio-fabricated and extracted processes*- Page 169

3.3.1.2. **Alternative approaches**

The non-renewable resources required for biocement are minimal in comparison to ordinary Portland cement. This is supported by the fact that rather than extracting limestone from natural sources to be processed, the specific microorganisms actually make it naturally. Biocement production which relies on this process requires the following common resources:

1. Microorganisms
Microorganisms, both bacteria and microalgae, are naturally occurring and capable of reproduction and can therefore be considered renewable as a resource. However, in the framework of more-than-human thinking and recognition of agency, we must give careful thought to how we view microorganisms as a resource, which could minimise rather than acknowledge their agency.

2. Calcium source
Calcium is a critical chemical element of calcium carbonate, therefore needs to be present for biomineralisation reactions to take place. However, none of the companies openly state the source or quantities of calcium sources required to facilitate their specific processes and therefore, while it must be considered, this resource is difficult to comment on.

3. Water
Water is a necessary medium to facilitate the biochemical reactions necessary for biocementation to occur. However, in these processes, much less water is required in comparison to conventional cement, and this water is able to be recycled at a much higher rate than in traditional concrete.

BioMason's production method in particular occurs due to the MICP method of urea hydrolysis, and therefore also requires urea. Urea forms naturally as the end product of the metabolic breakdown of proteins by all mammals, occurring mainly in urine, but also blood, perspiration and milk. Urea is now prepared commercially from liquid ammonia and liquid carbon dioxide (Encyclopedia Britannica, 2024). The urea source for BioMason's process is not openly stated, therefore its environmental impact is difficult to assess.

In the case of Prometheus Materials' process which uses photosynthetic microalgae, sunlight and carbon dioxide[30] are also necessary resources to support the metabolism of the microorganisms. Prometheus Materials has paid particular attention to their water consumption and boasts a highly water-efficient process, using significantly smaller amounts of water during production that OPC concrete, with up to 99% of water being recycled or returned to the atmosphere. The process is also not dependent on freshwater specifically and can utilise saltwater and even some wastewater which are abundant.

Basilisk's self-healing agent is primarily sold as an admixture to be added to varying concrete mixes. The resources it requires alone are therefore limited to microorganisms and nutrients, a source of calcium ions. Their premixed mortar (MR3) includes fly ash as a supplementary cementitious material, reducing the demand for limestone extraction. As the main benefits of Basilisk self-healing concrete are in extending the service life of concrete through its watertight and crack-healing properties, the use of the product may reduce resource consumption in other areas. Its watertight properties reduce the need for waterproofing membranes, and the crack-healing properties reduce the need for crack width controlling steel. By extending the durability and service life of concrete, it also reduces resource depletion through reducing maintenance and replacing requirements.

[30] See case study: *Urban Algae Folly*
ecoLogicStudio
Page 64-67

Table 06: *Comparison of cementitious materials approach to resources including bio-fabricated and extracted processes*

	Cementitious materials approach to resources			
Resources	**OPC Concrete**	**BioMason**	**Prometheus Materials**	**Basilisk**
Limestone	Extractive	Biologically generated	Biologically generated	Extractive, partially replaced with fly ash (MR3)
Aggregate	Extractive	Waste stream: Industrial waste stream aggregate (pre-consumer recycled content)	No specific data	No specific data
Water	Cement hydration: Water cannot be reused /recycled	Microbial processes: Requires less water than OPC, can be reused/ recycled	Microbial processes: Freshwater, saltwater, some wastewater. 99% recycled	Cement hydration: Water cannot be reused /recycled
Microorganism		Bacteria (*Sporosarcina pasteurii*)	Cyanobacteria / Microalgae	Bacteria (alkali-resistant*)
Nutrients		Calcium ions, urea	Calcium ions, sunlight, CO_2	Calcium ions (calcium lactate*)
Energy	High energy demand	Low energy requirement	Low energy requirement	Energy saved in use phase

* (Jonkers, Thijssen, Muyzer, Copuroglu, & Schlangen, 2010)

What makes fungi so unique as an inspiration in the light of new material investigations set in the context of an urgent need for environmental strategies, is that they have both the ability to break down an extensive range of organic and inorganic compounds, as well as the ability to reassemble them into hierarchical structures throughout different scales (Vélez, 2023, p. 13). These abilities make the metabolism of fungi a great ally in reducing the need for new raw material extraction and aiding in creating circular production processes.

The raw materials required for the production of mycelium composite materials include:

1. Mycelium

Mycelium for the production of mycelium composite materials can be sourced from spores, hyphal tissue or fruiting body tissue from existing fungi. As living, reproducing organisms they can be considered renewable as a resource. However, this too opens the space for critical reflection on the framing of microorganisms as resources during the production process.

2. Substrate

The substrate is the substance on which the fungi grows, lives and uses as food. Being the second main component other than mycelium composing this composite material, the substrate influences the properties of the mycelium composite material, as well as the environmental impact. Due to the ability of fungi to break down a wide range of organic and inorganic compounds, mycelium composite materials can aid in environmental remediation of organic materials such as invasive species and agricultural waste including straw, sawdust, husks or even textile residues (Mogu), and even go as far as decomposing inorganic waste such as plastic to produce useful products (Sheldrake, 2020, Van Rompaey, 2020).

3. Water

Water is required to initiate and sustain the growth of mycelium throughout the substrate as the moisture content must be controlled to create the ideal conditions for fungal growth. However, water use for the growing of fungi for both agricultural and construction purposes is substantially lower than traditional farming and building materials.

4. Nutrients

In some cases, additional nutrients (such as sugars or starches) may be added to the organic substrate to promote the growth of mycelium. However, many substrates from agricultural waste streams can usually supply sufficient nutrients on their own.

Ecovative Design has contributed substantially to research and development in this field, experimenting with different strains and substrates, which they use for a wide range of applications. Their MycoComposite products are grown using waste from agriculture and forestry as substrate, including hemp herds and aspen for the products under investigation in this analysis. On top of producing their own plastic-free packaging and insulation materials from waste stream bio-based materials, a large amount of mycelium material development is occurring under license from Ecovative, with over 40 patents in 31 countries on the fundamental art of mycelium materials (Haute Matter, n.d.). The scale of Ecovative Designs influence on the field of mycomaterials, and the mitigation of resource depletion, extends well beyond their own product range.

Mogu's acoustic panels are made from fungal mycelium and use upcycled textile residues, such as cotton, particularly the short, dusty fibers which cannot be used in upholstery or yarn production (Mogu), as a substrate. While they do not disclose more specific information regarding the sourcing and processing of their substrates, the company emphasises that they aim to utilise low-value residues from agro-industrial value chains (Mogu, 2019).

Table 07: *Comparison of insulative materials approach to resources including bio-fabricated and extracted processes*

	Insulation materials approach to resources			
Resources	**EPS**	**MycoHAB**	**Ecovative Design**	**Mogu**
Styrene	Non-renewable - Petroleum derived			
Expansion gas	Pentane			
Energy	125 MJ/kg (Lushnikova, 2016)	-	24 MJ/kg non-renewable (Ecovative Design, n.d.)	-
Mycelium		*Pleurotus ostreatus* (Oyster Mushroom)	-	-
Substrate		Destructive encroacher bush (bioremediation) - Acacia mellifera	Agricultural waste: Sawdust - Aspen Shavings, Aspen Chips, Hemp	Low-value, pre-engineered residues from agro-industrial value chains - textile residue
Water	Re-used - Steam	0.486 L/kg (Redhouse)	3.785 L/kg (Ecovative Design, n.d.)	-
Nutrients		-	-	-

- No data specified

33.

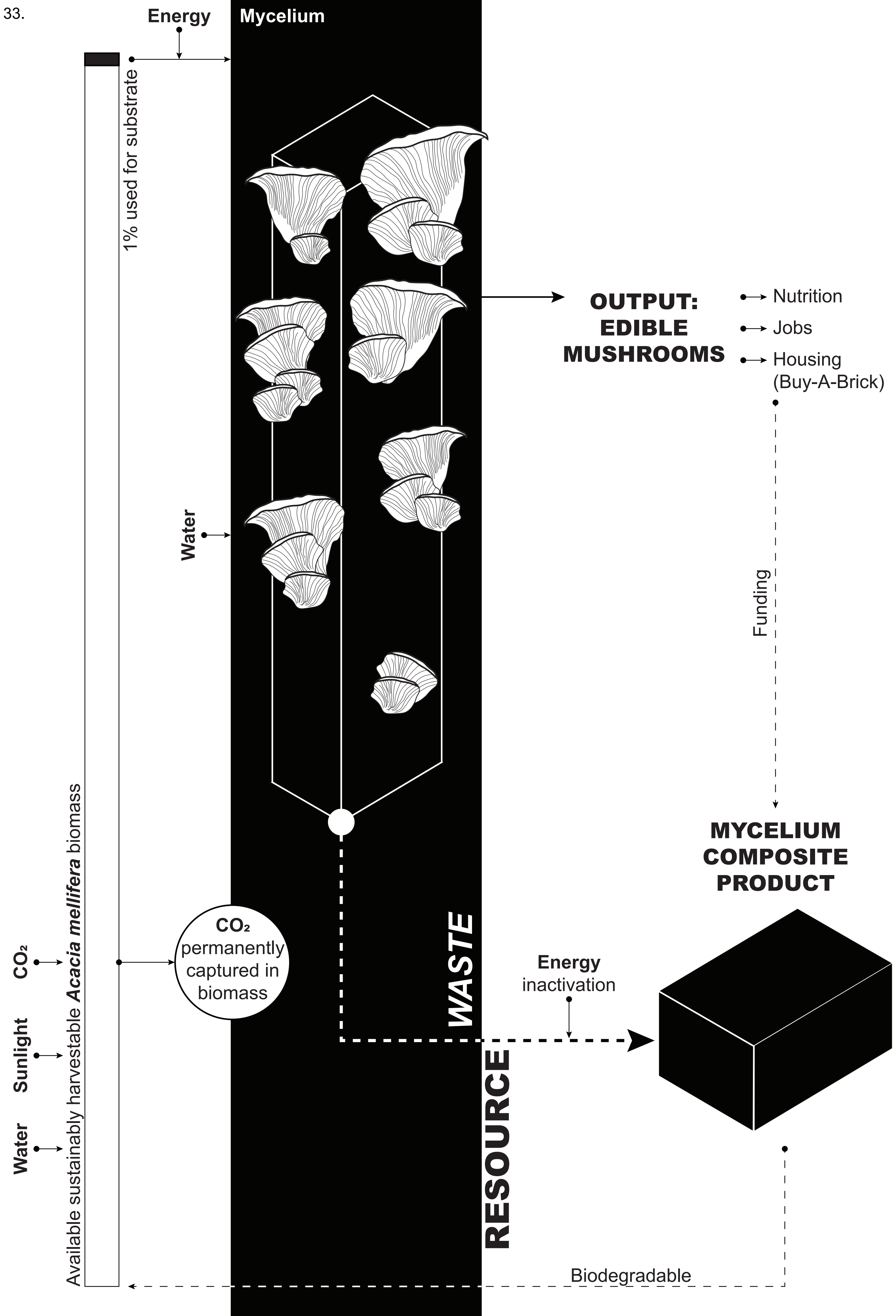

Figure 33. *Diagram of the MycoHAB's waste to resource approach and the mycelium metabolism:* Diagram by author, 2024

The process and products developed by MycoHAB encompass a multi-level resource and waste approach[31]. The first layer of production is the growing of edible oyster mushrooms. The main raw materials for their process are oyster mushroom spawn, which are renewable and easily accessible, and a substrate made by grinding a local destructive encroacher bush, the *Acacia mellifera*. The *Acacia mellifera*, or black-thorn acacia bush, is currently encroaching on wildlife refuge in the form of grasslands and natural aquifers in Namibia. It is reported that of this encroacher bush, Namibia has 330 million tons of biomass that can be sustainably harvested every 15 years (MycoHAB, 2022). If only 1% of the harvestable amount, 22,000 tons per year, was harvested through this process, MycoHAB estimates that 82,500 tons of edible mushrooms could be grown while fostering wildlife and increasing groundwater reserves (MycoHAB, 2022).

The 'waste' from this mushroom farming is then utilised as a resource in the second level of production, the MycoBlocks, where the mycelium inoculated substrate is pressed and fired into bricks. MycoHAB predicts that with the same 1% of the available biomass of Namibian encroacher bush, around 16,500 'mycoHABs' could be constructed creating 1600 jobs (MycoHAB, 2022). This data only accounts for using a small portion of the available, and necessary to remove, natural resources and has potential to be even more beneficial with larger numbers.

It was published by Redhouse Studio Architects that 13 tons of bush, 100 kg of mycelium and 6000 L of water to produce 3 tons of mushrooms as food and 950 MycoBlocks of 13 kg each (Redhouse). From this, we can calculate that per each kilogram of material, approximately 1 kg of substrate, 8 grams of mycelium and 0.485 L of water are required, and 1 kg of useful mushrooms are produced in the process.

[31] See figure 33: *Diagram of MycoHAB's waste to resource approach and the mycelial metabolism* - page 170

3.3.2. **End-of-life**

With life-cycle and cradle-to-cradle thinking, how a material is processed and what implications it has at the end of its service life are a fundamental consideration. This study assesses and compares biofabricated alternatives with conventional materials in terms of:

1. Durability and Biodegradability
Concerning how long the material lasts, both in service and landfills
2. Reuse, recycling and waste processing
Concerning how material waste is processed and the reuse and recycling potential
3. Toxicity and pollution
Concerning the lasting impact of the material on ecosystems encompassing of human and non-human life

3.3.2.1. **Standard practice**

Concrete

Durability and Biodegradability:
Concrete is a durable material, which can be made more durable with consideration of cement type, water to cement ratio, casting methods and curing. It is built to have a long service life which reduces the need for replacement and maintenance, however concrete does not last forever and can be damaged by cracking and water penetration, and therefore will at some point require maintenance or replacement.

When it comes to the end of its life, concrete is, due to its build for durability, inherently non-biodegradable and remains in the environment for a long time. Construction and demolition waste contribute significantly to landfill volume, contributing to long term environmental impact.

Reuse, recycling and waste processing :
The reuse potential of concrete depends on its form. Reinforced concrete, due to its monolithic composition, is impossible to dismantle for uses other than aggregate. On the other hand, concrete in the form of masonry units or pavers can be reused if not damaged during disassembly and the obstacle lies in the binding method rather than the material itself. If possible, the reuse of concrete elements without processing reduces the need for new material production, which is energy intensive and emits a large amount of carbon dioxide, as well as preventing the downcycling of the material.

It is considered common practice to recycle concrete by crushing it to be used as aggregates in new construction projects. However, the use of recycled aggregates can be energy and carbon intensive due to processing and transport and can also impact the properties of the new material meaning that it cannot completely replace natural aggregates for most structural applications, and often rather end up in landfills. Recycled aggregates absorb more water than natural aggregates due to their porosity, which results in reduced workability and mechanical properties for a given water to cement ratio. In order to achieve sufficient properties, more water is therefore required. While concrete can technically be recycled into lower-grade aggregates, it is often downcycled and used in applications where the material's properties are less critical such as fill or sub-base materials.

Toxicity and pollution:
When demolished, concrete generates large amounts of dust and particulate matter that contribute to air pollution and can be harmful to respiratory health. Additionally, the crushed debris leaches alkaline which can impact the pH levels of soil and water, posing long-term ecological risks, particularly for aquatic life forms (Keohane).

Given these challenges, there is a growing call within sustainable architecture to explore alternative materials and more efficient recycling methods to reduce the ecological footprint of concrete waste.

Durability and Biodegradability:
Clay bricks are renowned for their durability, often lasting hundreds of years with minimal degradation, making them a popular choice for long-lasting construction. Clay bricks have a high resistance to weathering and maintain structural integrity under various environmental conditions, including freeze-thaw cycles, UV radiation, and moisture exposure.

However, clay bricks are not biodegradable meaning that they do not break down naturally over time. Although they are made from naturally occurring materials like clay and sand the high-temperature firing process transforms it into a stable, inert material. As clay bricks do not decompose, their disposal in landfills presents a long-term environmental burden.

Reuse, recycling and waste processing:
When buildings are demolished, intact clay bricks can often be salvaged and reused in new construction projects due to their durability. Reused bricks retain their structural properties, making them valuable in reducing demand for new materials. Limitations to reuse occur due to damage during deconstruction and difficulty in separating bricks bound with mortar, especially if the binder is portland cement based.

If reuse is not possible, bricks can be recycled by crushing them into aggregate, which can be used in road sub-bases, landscaping, or as a component in recycled aggregate. As with recycled concrete, the use of crushed bricks as aggregate has an impact on the mechanical properties and water requirements of the resulting material and therefore needs to be used with consideration.

As recycling and reuse poses challenges, a portion of demolished brickwork does end up in landfills and due to their non-biodegradable nature, any clay bricks that do end up as waste in landfills will remain indefinitely. It is reported that 90% of crushed bricks can be reused, while the remaining 10% ends up in landfills, a scenario that is commonly used for life cycle analyses (The Brick Development Association, 2019).

Toxicity and pollution:
Clay bricks are generally considered non-toxic and safe for use in construction, as they are made from naturally occuring materials. As a result, they do not release harmful substances or gases under normal use, making them a non-toxic building material once installed. It is however important to consider any potentially toxic coatings, paints or treatments that bricks may have been subject to in the past. Although bricks remain intact indefinitely taking up landfill space when not recycled or reused, clay bricks themselves

are not toxic to humans or the environment, not do they release harmful substances.

However, the production process of clay bricks can contribute to pollution due to the energy required for the firing process, often powered by fossil fuels, which generates greenhouse gases like CO_2, as well as pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which contribute to air pollution and climate change.

Durability & Biodegradability:
A large portion of EPS insulation ends up in landfills. Due to its lightweight and bulky nature, EPS can take up significant space and, unfortunately, does not biodegrade, remaining in landfills for hundreds of years. Over time, EPS can break down into microplastics, posing risks to wildlife, humans and ecosystems.

Reuse, recycling & waste processing:
Recycling options for EPS insulation are limited. While EPS is technically recyclable, the infrastructure for recycling it is limited due to the cost and complexity involved in processing it. Complexity is often due to the separation of materials.
In some cases, EPS insulation may be incinerated. While this method can reduce the volume of waste, it can also release harmful emissions if not properly managed.

Toxicity and pollution:
EPS insulation has negative effects in terms of ecotoxicity, and even according to material safety data sheets from producers, “the product should not end up in the environment” (BEWi, 2021). The small particles which make their way into the environment, microplastics, can have negative physical effects on both aquatic and terrestrial organisms. They can also have inhibitory effects on the activity of micro-organisms (BEWi, 2021) which are critical to the functioning of healthy ecosystems and natural decomposition of waste (and the making of more sustainable material alternatives).

EPS has potential to release toxic chemicals upon combustion, or even through processing mechanisms such as hot wire cutting. These chemicals include carbon monoxide, carbon dioxide, styrene and aliphatic hydrocarbons (BEWi, 2021), which can be toxic to both humans and animals.

The natural decomposition of EPS over long periods of time can also release toxic chemicals such as pentane, styrene monomer, and carbon monoxide (BEWi, 2021). These chemicals are released into the environment while EPS sits in landfills causing negative effects.

3.3.2.2. **Alternative approaches**

Biocement

Reuse and recycling:

Like ordinary concrete, it can be assumed that the reuse potential of biocement is dependent on its form. As most available products are in the form of masonry units or tiles, it can be assumed that, depending on their assembly, they have the potential to be reused in their original form

According to the Living Future Institutes Declare label attributed to BioMason’s BioLITH tile, the product is “salvageable/reusable in its entirety, 100% recyclable” (International Living Future Institute, n.d.). There is however no specification on how biocemented materials are to be recycled and no known testing to demonstrate exactly each specific composition performs in comparison to ordinary concrete as a recycled aggregate. This is an area that requires further research and testing.

Durability and Biodegradability:

Biocement is not fully biodegradable. While calcium carbonate formed through process of MICP is a naturally occurring material, it is mineral-based and does not break down in the same way that organic materials do. The calcium carbonate produced by the microbes is a stable and durable mineral that can persist in the environment for long periods, therefore supporting a durable construction material.

In the case of Basilisk, the addition of bacteria to the cement matrix can actually improve the durability of the material through its water resistant and self-healing properties, reducing the need for maintenance and replacement.

Toxicity and pollution:

There is speculation around the use of bacteria due to the immediate association with pathogenic bacteria embedded through the anti-biotic revolution. The bacteria and microalgae used for the production of biocement are not dangerous and non-pathogenic for humans.

Basilisk contains bacterial spores from alkaliphilic spore-forming Bacilli, classified as group 1 bacteria which are defined by the European Parliament (2000) Directive 2000/54/EC on the protection of workers from risks related to exposure to biological agents at work as not dangerous and non-pathogenic for humans (Basilisk, 2019). In terms of ecotoxicity it is remarked on the Material Safety Data Sheet that Basilisk mortar is considered to be harmless for the environment since it does not contain dangerous substances. Based on the available toxicity data for individual compounds, it is not recognised for unusual toxicity to plants or animals. They do however mention that any negative environmental effect could be related to the alkaline nature of the portland cement rather than toxicity of components (Basilisk, 2019).

BioMason’s BioLITH tile obtained a Declare label, signifying that the product has been screened and declared LCB Red List Free. This indicates that 100% of ingredients present at or above 100 ppm (0.01%) in the final product do not contain any chemicals known to pose serious risks to human health and the greater ecosystem, known as Red List chemicals (International Living Future Institute, n.d.).

Mycelium composites

Reuse and recycling:

Mycelium composite materials have a fairly long service life if stored in the right conditions, therefore lend themselves to be reusable depending on how they are attached in their original construction. Mogu’s Foresta system, for example, showcases an installation of mycelium composite materials that can be easily disassembled and reused in a new location.

As mycelium composite materials are biodegradable, it has not been a focus to explore their recycling potential. It has however been noted that as an organic material, a mycelium composite panel can be recycled as substrate for new product formation. This is an area that could be explored further.

Durability and Biodegradability:
Mycelium composite materials are fully biodegradable at the end of their life, meaning that they can be broken down and metabolised by animals or microbes to become nutrition for the ecosystem (Ecovative Design, n.d.). On top of this, since fungi are nature's natural decomposers, mycelium composite materials have the potential to remediate inorganic waste through their growth process into a biodegradable material. Research has been conducted on the potential of certain strains of fungi to be able to decompose even plastic waste, and turn it into a useful, and ultimately biodegradable product (Sheldrake, 2020; Van Rompaey, 2020)

Ecovative Design shares that their Styrofoam replacement MycoComposites are home-compostable in 45 days, meaning that impacts from transportation (C2) and waste processing (C3) can be emitted entirely. Their products biodegrade in 30 days under industrial conditions, and 180 days in marine conditions (Ecovative Design, n.d.), leaving a much lower impact than plastic-based materials such as EPS and other Styrofoam products. This biodegradability however does not mean that the product is not durable, with a shelf-life of 30 years under the right conditions (Ecovative Design, n.d.).

Toxicity and pollution:
The mycelium composite materials in the study, composed of only organic matter, are 100% bio-based and non-toxic. While there is speculation around bacteria and fungi due to the anti-biotic society within which these materials emerged, the strains selected for the production of mycelium-based materials are non-pathogenic, and sometimes even edible. Due to their biodegradability, mycelium composite materials turn into useful nutrients for the soil rather than polluting ecosystems like their polymer-based alternatives. Ecovative Design has tested their products according to ASTM standards for VOCs (ASTM D5115-10) and aldehydes (ASTM E1333 & D5116-10) for which they both prove to be under limits. Their products are also USDA Certified Bio-based according to ASTM D6866 at 100% (Ecovative Design, n.d.).

Table 08: *End of life conditions of biocement and mycelium composite products in comparison to conventional building materials*

	End-of-life conditions							
	Recyclability & Reuse capacity		**Durability/ Biodegradability**			**Toxicity/Pollution**		
	Recyclability	**Reuse capacity**	**Durability/ service life**	**Home-composting**	**Industrial composting**	**Ecotoxicity**	**VOCs**	**Hazardous materials**
BioMason	100%	Salvageable/ reusable in entirety	Stable under standard conditions	No	No	-	Inherently non-emitting (Biomason, 2020)	Red List Free
Prometheus Materials	-	Reusable	Stable under standard conditions	No	No	-	Inherently non-emitting (assumed)	Nonpathogenic microalgae
Basilisk	Assumed as ordinary concrete	Spores lie dormant until activated, up to 200 years	Improved durability	No	No	Concrete alkalinity could have negative impact.		Not hazardous under EU regulations
MycoHAB	-	Reusable as product	-	-	-	Biobased		Nonpathogenic fungi
Ecovative Design	Biodegradable	Reusable as product or substrate	30 years	45 days	30 days	Biobased	Below limits	Nonpathogenic fungi
Mogu	-	Reusable as product	-	-	-	Treatment dependent	TVOC: 15 $\mu g/m^2h$ VVOC/SVOC: none	Nonpathogenic fungi
Control: CEM I ready-mix	Crushed for groundworks/ bulk material	Reusable as bulk material/recycled aggregates	100 years (Mineral Products Association (MPA) UK, 2024)	No	No	Fresh concrete may result in changes in pH Levels and may influence aquatic life forms. Hardened concrete has no ecological effects.	No	Hardened concrete is classed as non-hazardous and ‘inert’ Portland Cement (10-20%)): H315, 317,318, 335 Crystalline Silica: H372 (Hanson, 2021)
Control: Concrete tile (British Precast Concrete Federation, 2017)	90% recycle/ 10% to landfill	Suitable for disassembled effectively	50 years	No	No	When used as intended, no environmental impact is anticipated	No	Cutting of hardened products produces dust that will contain respirable quartz, this may constitute a chronic health hazard.
Control: Clay brick	Crushed for groundworks/ bulk material	90% reuse/ 10% to landfill (The Brick Development Association, 2019)	150 years (TBE, 2014)	No	No	No ecotoxicity (Wienerberger, 2018)	No	Hazardous ingredients: crystalline silica (quartz Si02) at 30-35%. Health risk may arise when dust is liberated in respirable form. (Wienerberger, 2018)
Control: EPS	Recyclable with limitations	Reusable with limitations	60 years (BEWI ASA, 2021)	No	No	Small particles may have physical effects on aquatic and terrestrial organisms, and inhibitory effects on the activity of microorganisms. The product should not end up in the environment.	-	Hazardous combustion products: carbon monoxide, carbon dioxide, styrene and aliphatic hydrocarbons. Hazardous decomposition products: Pentane, styrene monomer, carbon monoxide

- No specific data

3.3.3. **Energy consumption and carbon footprint**

Critical factors for determining environmental impact of materials are their embodied energy and carbon footprint. Carbon dioxide emissions have increased dramatically over recent history, leading to phenomena such as global warming with its resulting implications. A large portion of carbon dioxide is released due to the burning of fossil fuels and other industrial processes including the production of building materials. It is critical in this state of climate urgency to rapidly reduce carbon emissions and look beyond to ways that we can capture and store carbon.

This section explores ways in which biocement and mycelium composite materials have the potential to reduce energy consumption and carbon emissions in comparison to conventional building materials, and explore their carbon sequestration potential.

3.3.3.1. **Standard practice**

Concrete

Concrete is the second most used material, only following water. Due to this high demand, the current energy intensive and carbon emitting process contributes to a substantial portion of global totals.

The primary factor contributing to the carbon dioxide emissions of concrete is the production of the cement component. The production of portland cement in a traditional manner accounts for approximately 74-81% of the total carbon dioxide emissions of concrete whereas the aggregates only account for up to 13%. Therefore, when addressing carbon emissions of concrete productions, it is critical to focus on the cement component. Currently, ordinary portland cement (OPC) accounts for 7-8% of global carbon dioxide emissions, which is largely due to two key factors of the production process:

1. The calcination of limestone/Clinkerisation

The production of OPC requires the processing of raw materials including limestone ($CaCO_3$) and clay at high temperatures in a kiln. During this processing, the limestone decomposes and releases carbon dioxide. This alone contributes about 60% of the carbon emissions from cement production.

2. Processing energy demand

As the clinkerisation process requires a kiln of high temperatures, 1450°C, the energy demand is also high. When powered by fossil fuel energy, the combustion of these fuels releases further carbon dioxide into the atmosphere, making up the remaining 40% of carbon dioxide emissions from cement production. The cement sector is the third-largest industrial energy consumer, making up 7% of the global industrial energy use (International Energy Agency , 2018, p. 5).

According to CEMBUREAU, as of 1990 the CO_2 intensity of cement production came in at 0.89 tCO_2/ton cement (CEMBUREAU, 2024). Direct carbon dioxide emissions from the cement industry are expected to increase by 4% globally by 2050 according to the International Energy Agency (IEA) Reference Technology Scenario (RTS2) (International Energy Agency , 2018, p. 5) . However, in order to achieve a Net Zero Emissions by 2050 (NZE) Scenario, emissions need to fall by 3% annually until 2030 (IEA, 2023).

CEMBUREAU's Net Zero Roadmap projects that by 2030, there should be a 37% reduction in CO_2 emissions related to cement production, and 50% down the value chain and by 2040, a 78% reduction on cement, and 93% down the value chain, ultimately hoping to become carbon negative or even carbon neutral (CEMBUREAU, 2024). These are ambitious values for which reducing the demand for portland cement are critical.

With the existing composition of cement, it is possible to turn to alternative energy sources to reduce carbon emissions from the burning of fossil fuels, however the process of limestone decomposition, which contributes to the majority of carbon dioxide emissions, is considered to be near a minimum theoretical value, and no more savings are expected in Europe. Therefore, in order to address the problem of high carbon emissions from the large concrete and cement industries, alternatives are being explored to replace the carbon dioxide intensive process.

Strategies to limit carbon dioxide emissions include the addition of supplementary cementitious materials to partially replace portland cement and reduce the demand for the high emission processing. Supplementary cementitious materials include by-products of other industries including clay, pulverised fly ash, silica fume and rice husk ash. The addition of these materials can also impact the physical and mechanical properties of the cement such as durability, porosity and mechanical strength. Another strategy to reduce the demand for clinker is blast furnace cement, which is able to replace even higher amounts of portland cement.

However, these solutions do not mitigate the demand for portland cement entirely and may not be possible in the long term due to lack of availability, specifically blast furnace slag and fly ash. Therefore, novel solutions such as biocement are critical as they propose alternative, renewable binding methods that entirely replace OPC, and even offer potential for carbon sequestration in the process.

Clay Brick

Fired clay bricks are among the most commonly used building materials globally, however, their production process is energy-intensive and contributes significantly to carbon emissions.

The firing stage of clay brick production is particularly impactful, as it involves the combustion of fuels to achieve the high temperatures required. Clay bricks are typically fired at high temperatures, around 800–1100°C, which requires a large amount of energy to run. There are methods to reduce energy consumption such as optimised kilns, however energy is still required and traditional kilns are still prevalent for clay brick production, especially in developing regions.

The carbon footprint of fired clay bricks arises primarily from the combustion of fossil fuels and biomass as an energy source to achieve kiln temperatures. Additionally, the extraction and transportation of raw materials contribute to the overall carbon footprint.

While fired clay bricks remain a staple in construction, addressing their energy and carbon footprint, particularly in terms of firing temperatures and energy sources, or finding alternatives, is essential for advancing sustainable building practices.

Expanded Polystyrene (EPS) Insulation

Despite its benefits in reducing energy use in buildings over their lifetimes, the production of EPS requires energy and is associated with significant greenhouse gas emissions.

EPS is produced from polystyrene, a thermoplastic derived from petroleum or natural gas. The production involves the polymerisation of styrene monomers, followed by expansion using a blowing agent. The expansion process requires heat, therefore energy, often from the burning of fossil fuels, and the blowing agents themselves contribute to greenhouse gas emissions.

In the past, chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs) with high global warming potential (GWP) were used as blowing agents. However, in attempt to reduce global warming, pentane is now more commonly used. With a lower GWP, it significantly reduces the impact of EPS production, however it still contributes to greenhouse gas emissions as its GWP is not negligible.

EPS insulation can however offer significant carbon savings during its use phase by improving a building’s thermal performance and reducing operational energy demand for heating and cooling. However, if it is possible to replace EPS with lower-carbon alternatives while still achieving effective thermal insulation benefits, the impact can be even further reduced.

3.3.3.2. **Alternative approaches**

Biocement

Biocementation aims to replace traditional cementing methods which are energy intensive and carbon intensive in order to produce products that can be used as a replacement to traditional concrete. The production of biocement draws on the metabolism of microorganisms to respond to both factors of cement production contributing to large carbon emissions:

1. The calcination of limestone/clinkerisation
Rather than decomposing limestone to form portland cement which, as discussed previously results in a large portion of the carbon dioxide emissions from concrete, the biocementation process relies of microorganisms which produce calcium carbonate naturally without carbon dioxide emissions[32].

2. Processing energy demands
As this biocementation process occurs naturally at ambient temperatures, it cuts out the need for heating materials in a kiln at high temperatures. This substantially reduces the energy demand and therefore the carbon emissions from burning fossil fuels if such energy sources are used.

BioMason claims that their product, the BioLITH tile, offer the lowest carbon footprint cement tile on the market. However, FRONT Materials and BioMason acknowledge that there is still work to be done regarding cradle-to-gate carbon emissions, particularly regarding raw material supply chains (Stone Cycling). While exact numerical data on carbon emissions is not available, it has been reported that the process can reduce cradle-to-gate carbon emissions by more than 90% (Alliance for Low-Carbon Cement & Concrete, n.d.). Therefore, if ordinary portland cement has a CO_2 intensity of between 0.58 tCO_2/t (IEA, 2023) and 0.89 tCO_2/t (CEMBUREAU, 2024), the emissions of BioMason’s

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See figure 34: Carbon dioxide cycling of biologically generated versus extracted limestone
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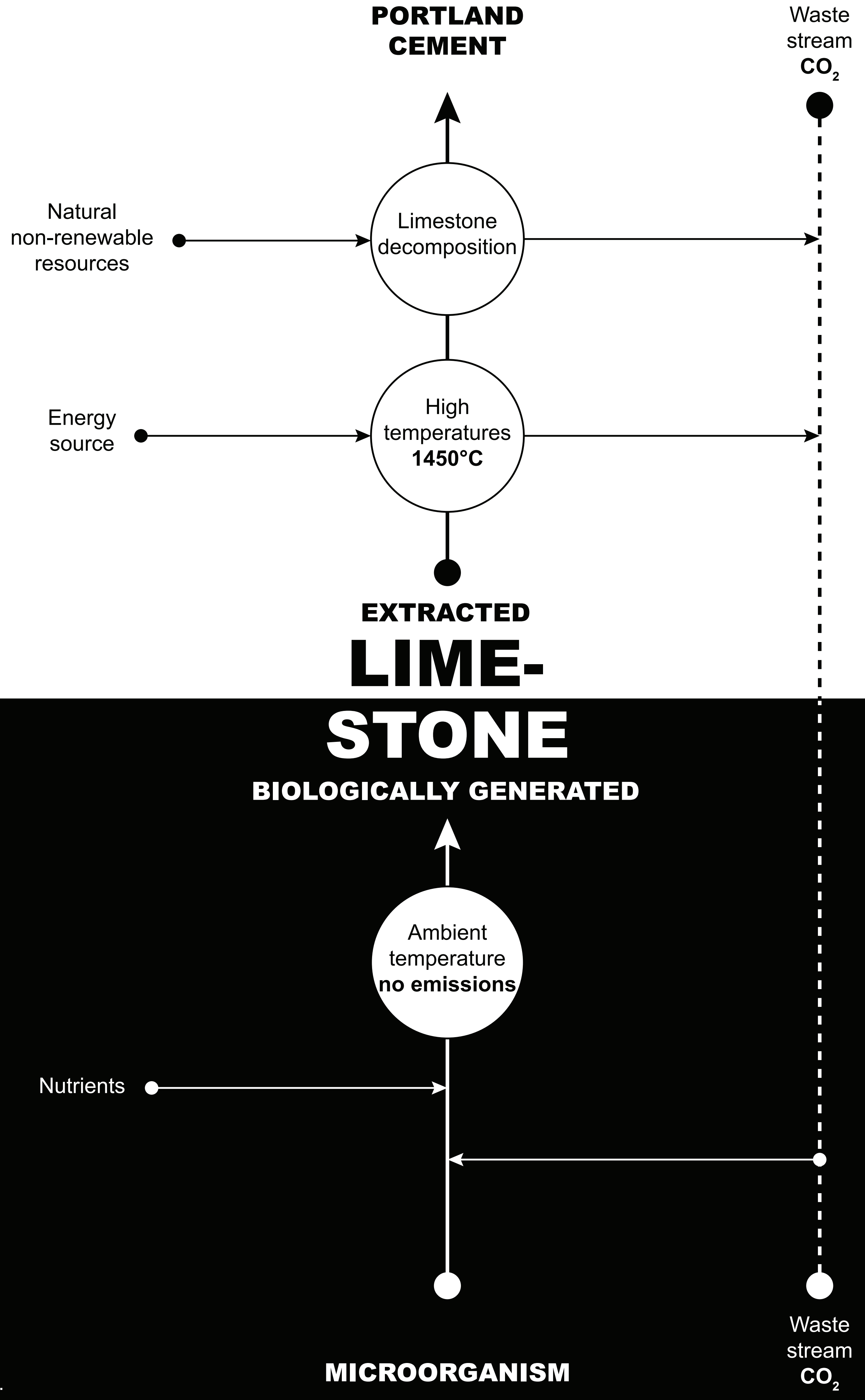
process are estimated between 0.058 tCO_2/t to 0.089 tCO_2/t, both well below the Net Zero Emissions (NZE) Scenario goal of 0.45 tCO_2/t set out by the IEA for the cement and concrete sector (IEA, 2023) and the projection of 0.44 tCO_2/t by 2030 and 0.062 tCO_2/t by 2040 as set out in the CEMBUREAU 2050 roadmap (CEMBUREAU, 2024). While achieving these values would require total replacement of conventional concrete, which is an unlikely scenario due to various limitations to be outlined further in chapter 4, even partial replacement can help guide the industry in the right direction to achieve its outline targets.

Prometheus Materials boasts net zero-carbon building materials, however the scope of this in terms of a life cycle approach and numerical values are not yet defined. The production process is aided by microorganisms, which in this case are photosynthetic cyanobacteria, as they metabolise to form a binding calcium carbonate without emitting carbon dioxide. In this case, sunlight and CO_2 are actually necessary nutrients to support the photosynthetic process. This method has the potential to reduce global carbon emissions by 8% if widely adopted (Prometheus Materials). While the product is still developing and has not yet been used in commercial applications, it has been tested in built projects such as SOM’s installation at the Chicago Architecture Biennial in 2023, the Bio-Block Spiral. It is predicted that by replacing traditional CMU with Bio-Blocks, this project alone reduces carbon emissions by one metric ton (SOM, 2023).

While still considered under the category of biocementation reliant on the metabolism of microorganisms, Basilisk’s self-healing concrete adopts a different approach to carbon emissions. Rather than reducing the carbon emissions in the production phase, the addition of an extra component to the concrete composition actually adds up to 20 kg of CO_2 per m^3 of material (Basilisk). The reduction of emissions comes in rather in later stages of the life cycle by extending the service life of the material due to the specific properties attributed to the material by the healing agent. Basilisk tested this through different scenario applications to estimate the potential carbon savings in the use stage of the material life cycle. Firstly, the addition of the healing agent reduces water permeability by 30%, resulting in a 30% increase in service life would reduce the necessity of casting new concrete to the same extent thereby reducing the carbon footprint of the product by 72 $kgCO_2/m^3$ (Basilisk). Secondly, the addition of Basilisk healing agent offers an alternative to membranes to make concrete watertight, whereby the carbon footprint would be reduced by an estimate of 18 $kgCO_2/m^3$ (Basilisk) in comparison to using a polyvinylchloride with plasticiser (PVC-P) water membrane. Finally, due to the crack healing properties attributed to the microorganisms, Basilisk both reduces the need for crack width controlling steel and maintenance and replacement due to damage caused by cracks. In this way, it is estimated that Basilisk can reduce carbon emissions by 66 $kgCO_2/m^3$ (Basilisk). In total it is estimated that, considering the volume of concrete for which water and moisture related durability is a concern being 660 million m^3/year, the implementation of Basilisk has the potential to reduce carbon emissions of the cement and concrete industry by 10 billion tons of CO_2 per year (Basilisk). Reductions due to service life extension are estimated to account for 70% of these reductions and reductions due to crack control accounting for the remaining 30% (Basilisk).

Basilisk also has their own CO_2 reduction calculation tool, the *Green-Basilisk Emissions Calculator*, available on their website, where you can tailor the amount of concrete, and healing agent (HA) to see how it impacts the carbon footprint of your project when using CEMIIA + HA in comparison to CEM I. The recommended dosage of healing agent varies between 4 and 7.5 kg/m^3 of concrete for precautionary purposes according to the product data sheet. Therefore, the resulting carbon emissions reduction according to the online tool is -25% for a dosage of 5 kg/m^3 (lowest possible value available on online calculator) and -23% for a dosage of 7 kg/m^3. While one may expect that a higher dosage of healing agent would result in greater reductions, this is not the case according to the calculation tool.

Due to their vastly different approaches and applications, it is difficult to compare the cradle-to-grave carbon emissions of all three materials in consideration without a more in-depth life cycle analysis. It can be noted that the biocementation process adopted similarly by BioMason and Prometheus Materials significantly reduces carbon emissions in the production manufacturing phase (A3) and can be considered more effective at reducing emissions through a cradle-to-gate approach, while Basilisk's self-healing properties and material enhancements contribute to emissions reduction during the use phase, particularly due to reduced maintenance (B2), repair (B3) and replacement (B4) requirements.



In the biological generation of limestone through microbial metabolism, carbon dioxide is used as nutrients rather than emitted as a waste stream product, as in standard practice. This significatly reduces the carbon footprint of the material as a reflection of natures self-remediating cycles.

Figure 34. *Carbon dioxide cycling of biologically generated versus extracted limestone:* Diagram by author, 2024

Table 09: *Biocement carbon emissions impact at life-cycle phases in comparison to conventional OPC products and clay bricks*

	Biocement carbon emissions impact at life-cycle phases in comparison to OPC products																	
	Production Stage			**Construction Process**		**Use Stage**								**End of life stage**			**Resource recovery**	
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water	De-construction	Transport	Waste Processing	Disposal	Reuse-Recovery-Recycling potential	Total
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**	
Clay Brick kgCO$_2$eq/kg *	0.213			0.008026	0.011466	■	■	■	■	■	■	■	■	0.000251	0.0032	0.00103	-0.016	0.324167
Concrete paver kgCO$_2$eq/kg **	0.131			0.0062	0.001	-0.0042	■	■	■	■	■	■	-0.00043	0.00346	-0.00160	0.00131	■	0.13574
Ready-mixed concrete C28/35 CEM I kgCO$_2$eq/kg ***	0.11429			0.00163	0.00205	-0.00622	■	■	■	■	■	■	0.00546	0.00026	-0.00916	0	-0.00739	0.10092
CMU	Extraction + water intensive	Mine to production transport	Limestone + energy	High density		■				■	Low thermal insulation	■	■	■			Mostly downcycled	
BioMason	-	-	-90%	x	x	■	x	x	x	■	Improved thermal properties	■	■	■	Red list free	100% recyclable	100% recyclable	-
Prometheus Materials	-	-	- 90%	- 85%	x	■	x	x	x	■	Improved thermal properties	■	■	■	-	x	x	-
Basilisk	-	x	+	x	x	■	Autonomous repair	Autonomous repair	Extended service life	■	x	■	■	■	x	x	x	-

** (The Brick Development Association, 2019), ** (British Precast Concrete Federation, 2017)

- Reduced emissions + Increased emissions x No known impact

Mycelium-based materials are grown rather than manufactured, typically using agricultural waste and other biological materials as a substrate which results in significantly lower embodied carbon compared to conventional building materials.

It is also important to consider the energy requirements to control specific conditions such as temperature, humidity and light to facilitate mycelial growth, as well as to inactivate the mycelial growth. As the fungi grows in dark conditions at ambient temperatures (Vélez, 2023, p. 101), the energy requirements for the growth process are minimal. The factor in the production process contributing to energy consumption is inactivation, which usually requires heat to stop fungal growth. However, in comparison to the high kiln heats of around 1450°C required for OPC production, the inactivation of mycelium composites only requires temperatures around 60-180°C (Sydor, Cofta, Doczekalska, & Bonenberg, 2022; Vélez, 2023, p. 24) depending on the heating time and specific application.

Ecovative Design reports that for the production of their MycoComposite product as a replacement for Styrofoam packaging, 77% of the energy required comes from renewable energy sources, with only 24 MJ/kg of product from non-renewable sources. This implies that the material requires around 104 MJ of energy in total to produce one kilogram of mycelium composite material, but the company is making an effort to use renewable energy sources. While there is no specific data on Ecovative Design's mycelium composite materials for construction purposes in terms of energy consumption, it can be assumed that the values will be similar as the material production process and outcome is the same.

Similarly, the global warming potential, or kilograms of carbon dioxide equivalent, per kilogram of material is reported to be 2.6 $kgCO_2eq/kg$ for Ecovative Design's MycoComposite 027.

MycoHAB's MycoBlocks are considered to be carbon negative due to the low energy requirements and carbon emissions, and the high carbon sequestration potential. The growth of the mushroom occurs at ambient temperatures without lighting demand, requiring minimal energy with minimal emissions. After this, energy is required to compress and heat the blocks, but temperatures are substantially lower than OPC production at only 140°C (Redhouse).

Another benefit in terms of reducing carbon emission through MycoHAB's process is the reduction of carbon emissions during the transport phase. It is estimated that for an average home (assuming 200 tons of material at an average transport distance of 300 km) would emit 4.2 tons of CO_2eq from transportation of the materials alone (MycoHAB, 2022). As MycoHAB proposes a system where materials can be grown on site, they estimate that if even only 1% of the world's materials were produced locally in this manner, that 1 million tons of carbon dioxide emissions could be avoided in the transport alone.

While there is no information published by Mogu considering their carbon emissions, it can be considered that since it uses the same production principles as Ecovative Design and MycoHAB along with general literature regarding mycelium composite production, that carbon emissions would be similarly low in comparison with other conventional building materials, with the potential of being carbon-negative.

Table 10: *Mycelum composite carbon emissions at life-cycle phases in comparison to EPS insulation*

	Mycelium Composite carbon emissions at life-cycle phases in comparison to EPS insulation																
	Production Stage			Construction Process		Use Stage							End of life stage				Resource recovery	
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Re-furbishment	Operational energy	Operational water	De-construction	Transport	Waste Processing	Disposal	Reuse-Recovery-Recycling potential	Total
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	
EPS kgCO$_2$eq/kg *	3.8675			0.196									0.00	0.0558	3.1675	0.000061775	-0.0156	7.2712
Ecovative Design	Capture/ waste	Locally sourced	-	x									x	Eliminated	-	-	Bio-degradable	2.6 kgCO$_2$eq/kg
Mogu	Waste stream	x	-	x									x	-	-	-	Bio-degradable	-

Table 11: *Structural mycelum composite carbon emissions at life-cycle phases in comparison to clay bricks*

	Mycelium Composite MycoBlock carbon emissions at life-cycle phases in comparison to concrete & clay brick																	
	Production Stage			Construction Process		Use Stage							End of life stage				Resource recovery		
	Raw material supply	Transport	Manufacturing	Transport	Construction installation	Use	Maintenance	Repair	Replacement	Re-furbishment	Operational energy	Operational water	De-construction	Transport	Waste Processing	Disposal	Reuse-Recovery-Recycling potential	Total	
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D		
Clay Brick (Wiener-berger) kgCO$_2$eq/kg **	0.25555			0.0125	0.0928								0.00054	0.00172	0.00	0.0161	-0.00366	0.37555	**landfill**
														0.00104	0.00263	0.00	-0.00612	0.35894	**recycle**
Clay Brick (Sector) kgCO$_2$eq/kg ***	0.213			0.008026	0.011466									0.000251	0.0032	0.00103	-0.016	0.324167	
MycoHAB	Capture/ remediation	Locally sourced	tbc	Eliminated	x						Increased insulation			-	-	-	Bio-degradable	-	

* (BEWI ASA, 2021), ** (Bauen mit Backstein Zweischalige Wand Marketing e. V., 2016), *** (The Brick Development Association, 2019)

- Reduced emissions, + Increased emissions, x No known impact

3.3.3.3. **Sequestration and offsets**

On top of reducing production emissions, development of materials aided by the metabolism of microorganisms such as biocement and mycelium composites have potential for carbon capture and sequestration to further reduce the carbon footprint of the construction industry.

Carbon sequestration in building materials refers to the process by which materials capture and store carbon dioxide from the atmosphere or industrial emissions, preventing it from contributing to climate change. This sequestration can be either biological, where natural processes capture CO_2 (such as in plants and biomaterials), or chemical, where carbon is trapped in a stable form (like in certain types of concrete).

On top of this, some of these companies have selected to buy into carbon and energy offset schemes in an attempt to further reduce their environmental impact. Carbon offset credits and energy offset credits are market-based tools designed to compensate for emissions or energy usage by investing in projects that reduce or produce cleaner energy elsewhere. These credits allow individuals, companies, or governments to "offset" their environmental impact, particularly when they can't fully eliminate their emissions or energy consumption.

During the process of calcium carbonate precipitation through MICP, carbon dioxide is absorbed and incorporated into the calcium carbonate structure. This means the material is not only avoiding CO_2 emissions but also storing carbon within its structure. Once carbon is trapped in the form of calcium carbonate, it is stable and can remain sequestered for as long as the material remains intact.

It is noted that the calcium carbonate biocement, produced with the help of bacteria, developed by BioMason, contains 44% sequestered carbon dioxide by mass, which is obtained from industrial sources (Stone Cycling). The biocement makes up 15% of the total mass of the tile, meaning that the tile itself contains 6.6% sequestered carbon dioxide. The other 85% of the mass is composed of unspecified industrial waste stream aggregates (pre-consumer recycled content).

On top of the reduction in carbon dioxide emissions inherent in the production process, BioMason has publicised that they have selected to purchase carbon credits to offset the remainder of their emissions and energy use. The director of circularity at BioMason, Troy A. Hottle, announced in 2022 that “Biomason’s bioLITH line of products is now supported by 100% renewable energy and carbon offsets for all cradle-to-gate climate emissions” (Hottle, 2022). In order to achieve this objective, the company is voluntarily purchasing 12 MWh/month of Green-e Energy certified Renewable Energy Credits, and 9 metric tons/month of Carbon Offsets through terrapass, which they claim exceeds 100% of the process electricity and embodied carbon associated with the production of the BioLITH tile. In the same announcement, the director also claims that as production scales, BioMason will also improving their process efficiency and adjusting their renewable energy portfolio accordingly to meet their sustainability commitments to themselves, their customers and the environment (Hottle, 2022).

Prometheus Materials on the other hand utilises photosynthetic microalgae, which have the capability to sequester carbon at a much larger scale. While there is no available data on the precise amount of carbon that can be sequestered, it is estimated that the products ability to sequester carbon during the production process enables it to reduce embodied carbon by 90% in comparison to existing portland-cement based products (Prometheus Materials, 2022).

Basilisk self-healing concrete does not claim to sequester substantial amounts of carbon dioxide as the precipitation of calcium carbonate by bacteria is only activated when cracks appear and water penetrates the concrete, and only occurs on a small scale to fill cracks.

Mycelium grows on a substrate of organic matter, such as sawdust or agricultural waste. The carbon in this organic matter is captured through the process of photosynthesis of the plants during their lifetime. As the mycelium grows and forms a solid composite, it effectively locks in this carbon within its structure rather than releasing in into the atmosphere, effectively sequestering the carbon in the material. Fungi themselves respire rather than photosynthesise, however the carbon released by the organisms themselves is negligible in comparison to the positive impact they have on sequestering carbon through the fermentation process.

MycoHAB claims, through their process, to be able to store 1.5 $kgCO_2/kg$ material due to the organic substrate utilised.

The length of carbon storage is limited depending on how the material is processed at the end of its life. If mycelium composites are burned, the sequestered carbon is released back into the atmosphere, however, if the material is recycled or composted correctly, nutrients, including carbon, embedded in the material are returned back to the earth.

3.3.4. **Conclusion**

Biocement and mycelium composites as construction materials go to show that working with nature can help us produce in a way that benefits both humans and nature in the process. These materials offer benefits in terms of reducing resource extraction, improvements in end-of-life conditions and reduced carbon emissions, or even carbon sequestration.

The study of both of these material types also goes to show that there are many different approaches to sustainability, and it is not a one sise fits all solution, and that individual considerations need to be applied to each context.

The main benefits of biocement lie in the significant reduction of limestone extraction and processing and related carbon emissions by biologically producing a cement-like binder to produce materials with properties comparable to concrete. Biocement produced by photosynthetic cyanobacteria propose even more benifits in terms of carbon sequestration, using CO_2 as a source of nutrients for the biomineralisation process. While this still requires development to fully replace conventional concrete, it proposes new opportunities and a promising path forward.

Biocement, through self-healing, is also able to improve durability of existing concrete structures. While this still currently requires the use of portland cement, it can significantly reduce the need for maintenance and replacement, reducing material demand. There is also opportunity for including these self-healing properties into biocement elements, however this is still to be explored.

The benefits of mycelium composites, on the other hand, lie in its biodegradability, substantially minimising pollution, toxicity and contribution to landfill mass typical of conventional alternatives such as EPS insulation. Mycelium composite materials, in theory, can disappear without a trace, helping reduce human impact on the planet in terms of pollution. They also reduce resource consumption and carbon emissions, and have the added benefit of being great thermal insulation materials, which helps reduce energy consumption due to heating and cooling of buildings.

However, with this in mind, one must be vigilant not to entitle biocement and mycelium composites as silver bullets to solve environmental issues. Even though these materials are much lighter on the planet's systems than their conventional alternatives, the mass production of any specific material has the potential to interfere with natural systems. We do not yet know the implications of the mass use of specific resources, or quantities of materials left in the environment on the complex and intricate systems of the planet and must be careful with our tendency to meddle with nature. The following chapter will try to understand a way forward for the scaling and integration of biocement and mycelium composite materials in a way that is practical, sustainable and ethical for all species in a culmination of the three-dimensions of this work.

4. THE FUTURE

Three-dimensional considerations for addressing integration limitations

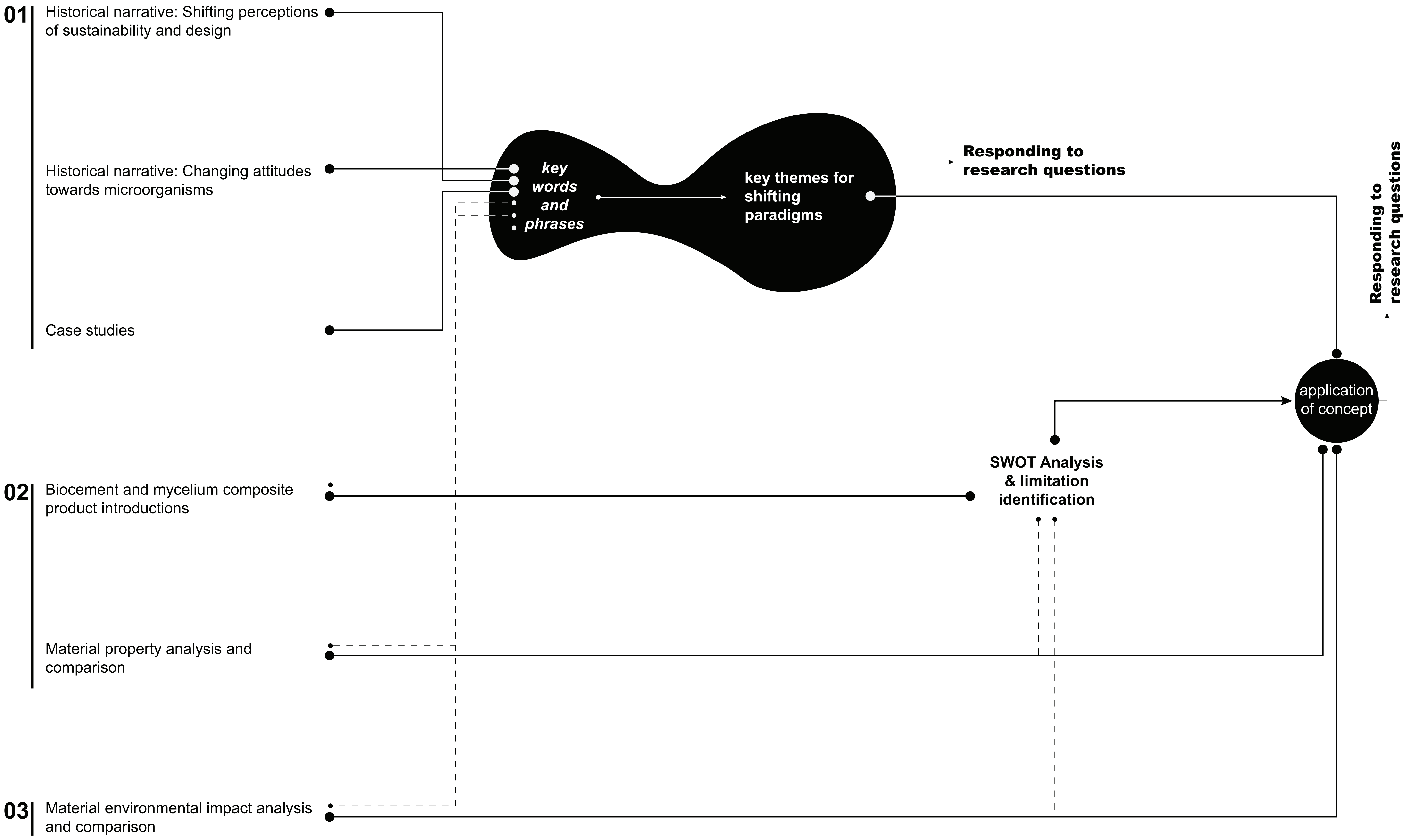
This chapter looks forward to the futures of biocement and mycelium composites within a complex and multi-dimensional context.

Through a three-dimensional analysis it becomes evident that these materials are not only shaping a new technical and environmental perspective, but also shifting paradigms within the fields of design, architecture and construction material production ethics through human-nature and interspecies relations.

By synthesising key words, from the three dimensions of the analysis previously conducted, was possible to identify key themes, or paradigm shifts, brought about by reflecting on the integration of living organisms into material production. These key themes respond to the research questions outlined at the beginning of the work:

> ***1. What multispecies ethical considerations arise from the historical and current use of microorganisms, particularly in architectural materials, and how can these inform more conscious production practices?***
>
> ***2. How can this way of thinking about production, fostered by multispecies collaboration, reshape architectural practices?***

To further elaborate on the themes and respond to their role in the future of biocement and mycelium composite materials, they will be applied, in overlay with technical and environmental considerations, to addressing the key limitations to the widespread integration of the materials in common architectural practice. This roadmap, or future speculation, aims to provide a toolkit of practices and considerations for a practical way forward, giving due value to technical, environmental and multispecies dimensions of architecture and material production.



01.

Figure 01. *Diagramatic representation of chapter four workflow connecting the three-dimensions.*

4.1. **The paradigm shift**

In order to effectively address the practical, ethical and environmental challenges associated with the scaling and widespread implementation of biocement and mycelium composites, let us look back to the analyses conducted in the previous sections to identify the key themes.

Tracing the narrative of the framework within which these materials emerged, with a focus on human and non-human relationships, allowed us to observe changing perceptions of sustainability in design paralleled with changing perceptions of microorganism, natural and synthetic production and the way we view the world and our human positionality within it. Viewing these parallel narratives through a more-than-human lens exposed the interconnections between disciplines and species through practical materiality, as changing multispecies relationships and understanding influenced design and architectural practices, particularly situated in a time where climate concerns drive new ethical frameworks. When overlayed with technical and environmental comparison of biocement and mycelium composites with conventional building materials, a new set of key themes[33] for material production and architectural discourse comes to the surface in light to the following research questions:

1. What multispecies ethical considerations arise from the historical and current use of microorganisms, particularly in architectural materials, and how can these inform more conscious production practices?

2. How can this way of thinking about production fostered by multispecies collaboration reshape architectural practices?

---

[33] See figure 02: *Thematic mapping of key words for identifying key themes for paradigm shifts regarding the furure of design practice and multispecies ethics - page 214-215*

4.1.1. **Key words for shifting paradigms**

Reflecting on the body of work conducted across the three dimensions, the following key words guide the formation of key themes for discussing the paradigm shifts brought about by integrating living organisms into material production:

Aesthetic – see also: *language*
Aesthetics refers to the visual qualities or design language represented through a design or artwork. In this case, materiality largely impacts the aesthetics of architecture, as well as design processes and decisions.

Agency – see also: *autonomy*
To have agency means to have the ability to actively choose a course of action, or the feeling of control over one’s actions. In this context, agency is explored regarding both human and non-human agents in the design and making process.

Applications
Applications refers to the different ways in which a specific material can be used or implemented in design and architecture. In the previous investigation, only conventional applications and replacement of existing materials has been considered, but applications enabled by interspecies collaboration could well extend beyond.

Architect – see also: *designer*
An architect traditionally is the designer and planner of buildings. However, in this context, the role of the architect is being pushed beyond conventional boundaries through more-than-human interactions. The role of the architect can also be questioned to what extent it is primarily a human action, and whether non-human agency enables more-than-human architectural agents.

Autonomy – see also: *agency, organisation*
Autonomy, similarly to agency, related to the right or condition of self-government. Autonomy is expressed in architectural history through self-sufficient buildings and ideas of circularity. Autonomy is also explored in more-than-human actors, through the ability of microorganisms to metabolise and produce material independently of human intervention.

Backgrounding – see also: *other*
Backgrounding refers to the overlooking of the ‘other’. Over the course of history, many cultures and belief systems have been backgrounded in favor of a dominant rational Western male culture. Similarly, the agency of non-human beings has been backgrounded in favor of human-centric design and planning.

Barrier – see also: *other*
A physical or conceptual divide between environments or entities. Historical tendencies in architecture and health practices lean towards creating barriers between humans and selected non-humans deemed ‘unhygienic’ or ‘other’.

Complexity
This multi-dimensional study explores the complexity of the intricate, interconnected nature of the planet through interspecies relations. Rationalist thinking, and other historical design practices, tend to avoid unnecessary complexity and ambiguity in favour of scientific rational explanation and simplification. On the other hand, microorganisms and interspecies interactions opens the idea of embracing complexity and ambiguity as an integral part of ecosystem functioning.

Control – see also: *power*
The historical drive in architecture and health has been to dominate and manipulate nature as an ‘other’. Control is evident in design practices and an integral part of shifting the narrative of the human-nature relationship.

Craftsmanship – see also: *process*
Craftsmanship represents a design quality shown in something made by hand. The human-touch has historically brought man closer to his roots, or even through some practices described to bring man closer to nature. Craftsmanship brings to question a specific aesthetic as well as the ability of more-than-human agents to ‘craft’ or make in their own right .

Designer – see also: *architect*
The designer is defined as a person who plans the aesthetic or function of something before it is made. In this context, the subject of the designer is questioned beyond a primary human role, as the metabolism and autonomy of microorganisms influences both the aesthetic and properties of materials.

Environment – see also: *locality, surrounding*
The natural world is often referred to as the environment, however in this context, environment primarily refers to the surrounding or context within which a being, design or building exists and operates. The environment and locality of material production is even more significant when considering the resources and geopolitics of materials produced through interspecies relations.

Labour
Labour refers to the workforce, particularly physical work. This investigation observes the conception of labour beyond a human workforce and explores the ethics and integration of living organisms into material production.

Language – see also: *aesthetic*
Language refers to both the way in which design ideas are communicated, often represented through a specific aesthetic, and opens the question of if and how different species can communicate to live and work together collaboratively.

Local – see also: *environment, surrounding*
Focuses on site specific characteristics and resources. Localised design comes into question when considering if common material practices, both conventional and novel, can be applied globally or if they need to be adapted to local environments in terms of resources, aesthetics and processes

Natural – see also: *organic, resources*
Referring to resources, materials or even aesthetics derived from 'nature'. Exploring what it means to be natural covers topics of synthetic reproduction, what it means to be from nature/natural and the exploitation of nature through resources, aesthetics, processes and systems.

Organic – see also: *natural*
Organic, in reference to materials, refers to materials that are from nature, or 'natural', however this concept is often ambiguous and controversial at times. Organic is also represented through a specific design language or aesthetic in an aim connect design with nature.

Organis-e/ing – see also: *autonomy, power*
The structuring of the design or production process. Organisation also refers to a mechanism of control, or contrarily autonomy through the self-organising capacity of both human and non-human agents.

Other - see also: *backgrounding*
A group that is viewed or treated as intrinsically different from and alien to oneself. In this context, from a human-centric perspective, nature or non-human beings are often treated as an 'other', therefore often resulting in a distinction from and capacity to control without sufficient recognition of the agency of such groups.

Ownership
The act or right of possessing something. Ownership refers to beings, knowledge and resources, and brings up ethical considerations regarding the relationship between human and non-human players and the physical and intellectual property of material production.

Power - see also: control, *ownership*
The capacity to exert control over others, expressed in the dynamics of the human-nature relationship through rationalisation, control and ownership. Power has the ability to influence domination of one group over another.

Process
Design, particularly in collaboration with more-than-human beings, inspires an emphasis on process rather than product, changing architectural practices in a way that places greater importance on the way that things are produced and the impact thereof.

Resource
The raw materials and other inputs that are required in order to produce. Exploration of resources explores ethical and environmental considerations regarding sourcing, usage, and regeneration, as well as roles and organisation within production processes.

Scale
Scale, or scalability, refers to the capacity to expand considering practical and ethical limitations.

Surrounding – see also: *environment, local*
The immediate ecological and physical environment within which a design or product is located.

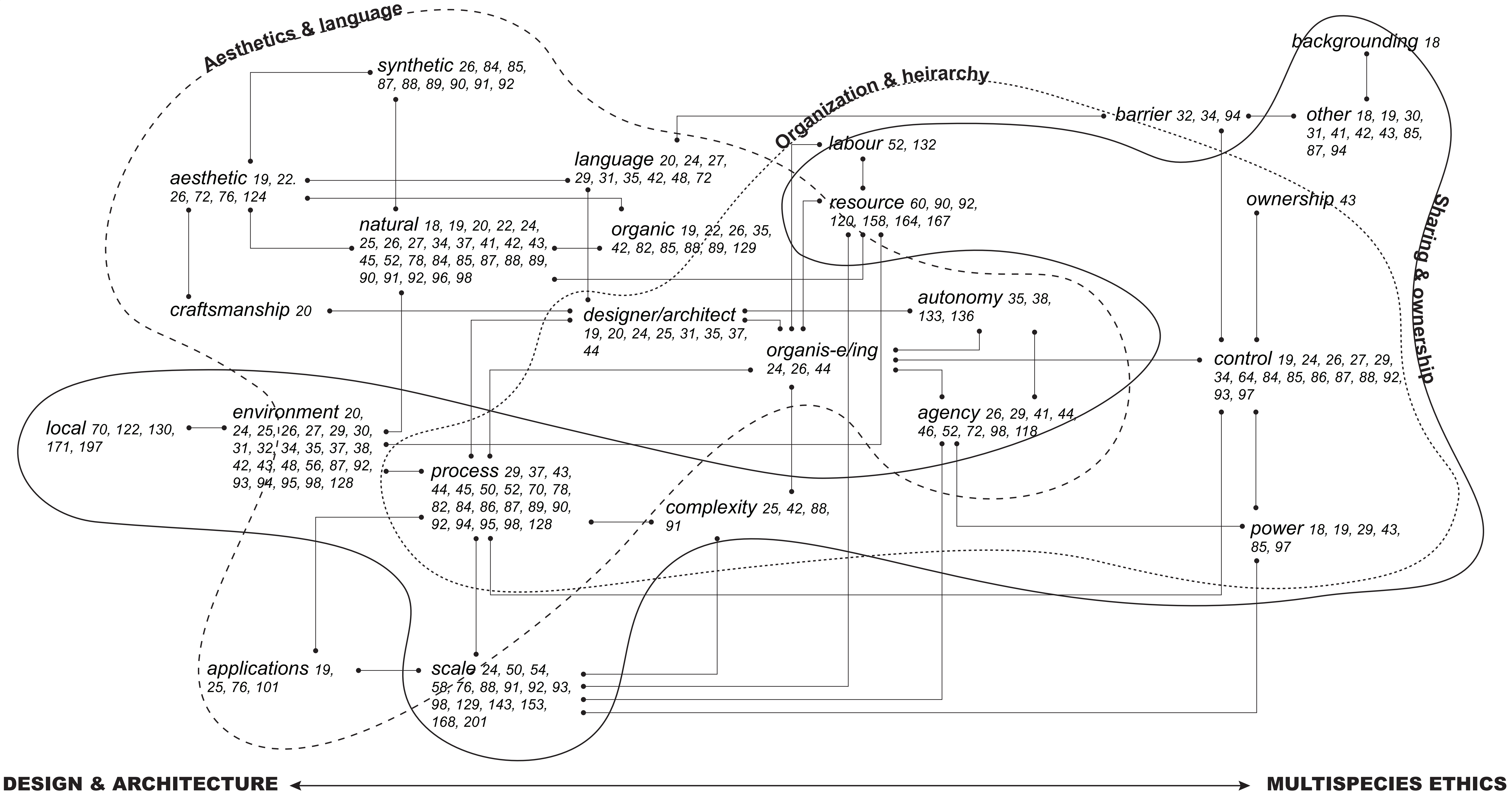
Synthetic - see also: *natural*
Referring to that which is not ‘natural’, or things which are engineered by humans. With technological development across disciplines, and a deeper integration of biomimetic principles in design process, the distinction between natural and synthetic comes to play, particularly in reference to biomaterials and their environmental impact.

Figure 02. *Thematic mapping of key words:* to idenitfying key themes for paradigm shifts regarding the future of design practices and multispecies ethics

Tracing the narrative of these key words, the following key themes for shifting paradigms that are integral to the consideration of the upscaling and integration of biocement and mycelium composites are:

1. Sharing and ownership
2. Aesthetics and Language
3. Organisation and heriarchy

02.



4.1.2. **Shifting paradigms in architecture**

As identified from a thematic analysis of key words identified from the complete body of work, the following themes identify critical paradigm shifts within architecture and material production brought up by a three-dimensional investigation into biocement and mycelium composites. These themes set the groundwork for addressing the future of these materials to follow.

1. Sharing and ownership
The theme of the ownership, or sharing of knowledge, within material production and architectural practices is a paradigm that is being shifted by the incorporation of microorganisms into material production and architectural investigations.

The interdisciplinary nature of the development and production of these types of materials brings architecture and design into contact with alternative, more organic methodologies of growth and development that promote collective knowledge rather than the safe holding of information.

Having to collaborate with non-human beings too makes architects and engineers question their own agency, control and ownership of the production process, handing a large portion of the key labour, and design development to some extent, to non-human microorganisms such as bacteria, cyanobacteria or fungi.
This theme will be expressed further in relation to the challenges presenting specific material examples in the following pages.

2. Aesthetics and Language
Similarly, the incorporation of microorganisms into architectural materials is reshaping perceptions of beauty, and inspiring a new architectural language through process, form and materiality.

As we form closer relationships and deeper understanding of the nature of microorganisms themselves, paradigms in other disciplines including health, agriculture and food production are shifting in a probiotic direction, recognising that not all bacteria are enemies, but can actually be allies. What has been coined as the *microbial turn* (Paxson & Helmreich, 2014) or *probiotic turn* (Lorimer, 2020), expressed across disciplines, reflects a paradigm shift in a way we understand the world and our sense of self within it. Even in architecture, the way in which we design buildings is shifting away from the clean, unornamented and hygienic spaces emphasised through modern architecture as an anti-bacterial response. With further scientific discoveries, we are learning that it is this this very act of shutting out bacteria and persistent cleaning that is causing a plethora of new illnesses and conditions. Even the sick building syndrome paradoxically emerges from the artificial systems intended to keep modern buildings ‘clean’ and isolated. Through new paradigms of knowledge and understanding, or so-called *probiotic turn*, is changing our perception of what ‘healthy’ buildings should be, when buildings are considered an integral part of the human ecosystem (Colomina & Wigley, 2021). Whereas before health, represented through clean, white, sterile surface, was inseparable from beauty, now changing understandings of health are therefore shifting the notion of beauty in architecture too.

In the same vein, when considering the human ecosystem, we now know that microorganisms too are not separable from ourselves, and that all species and life on earth are made up of complex interspecies relations. These complexities foster a sense of curiosity within us, now dealing with an undiscovered world that is at the same time a mystery to us and part of our own being. The microbial world is so vast and still unexplored, fostering a sense of curiosity and adventure. As we uncover more about these invisible yet entangled worlds, and ourselves in the process, a sense of inspiration is provoked for new unexplored architectural processes and expressions.

Through the uncovering of these hidden worlds, there is also a deepened appreciation for microbial growth through the arts too. Recognising the importance and agency of microorganisms as makers of worlds, and therefore art, the associated visuals that may previously have been conceived as infectious, disgusting or scary are now being viewed through a new lens as complex, interesting, and maybe even beautiful expressions of the untapped microbial world.

The conception of language also brings to question our capacity to communicate with the non-human entities, which are here integral to material production for a more collaborative and sustainable future. If we are designing for or with non-humans, do we have any real means of understanding or communicating with them? Designers in this field are exploring and interpreting new ways of understanding and interpreting non-human life through the aid of bio-digital technology and observation. These methodologies can enable more symbiotic relationships with more-than-human species and the planet itself, as well as shaping a new bio-digital aesthetic in their own right.

3. Organisation and hierarchy

Working in this manner with non-human actors brings forward ethical considerations in terms of production hierarchy and organisation regarding the agency of non-human actors. Exploring these considerations can bring about critical paradigm shifts towards more collaborative futures beyond the human species.

Critical to this exploration is the consideration of the capacity and implications of non-human agents within the roles of resource, labour and architect or designer. These categories, in a human context, define how agents are treated and compensated and can result in discriminatory or exploitive practices. Working so closely with non-human beings, showcasing the capacity for each of these roles, invites a deeper exploration and appreciation of the agency of non-human life and can enable a sense of empathy, steering us away from exploitive practices as seen in the past and foster a better approach to resource and labour practices.

I do not claim to have the answer to these complex relations, however, promote that their exploration is critical in working to more collaborative, non-exploitive and sustainable futures for material production. Therefore, I hope only to highlight some key thinking points and to promote further exploration through the following graphic novel.

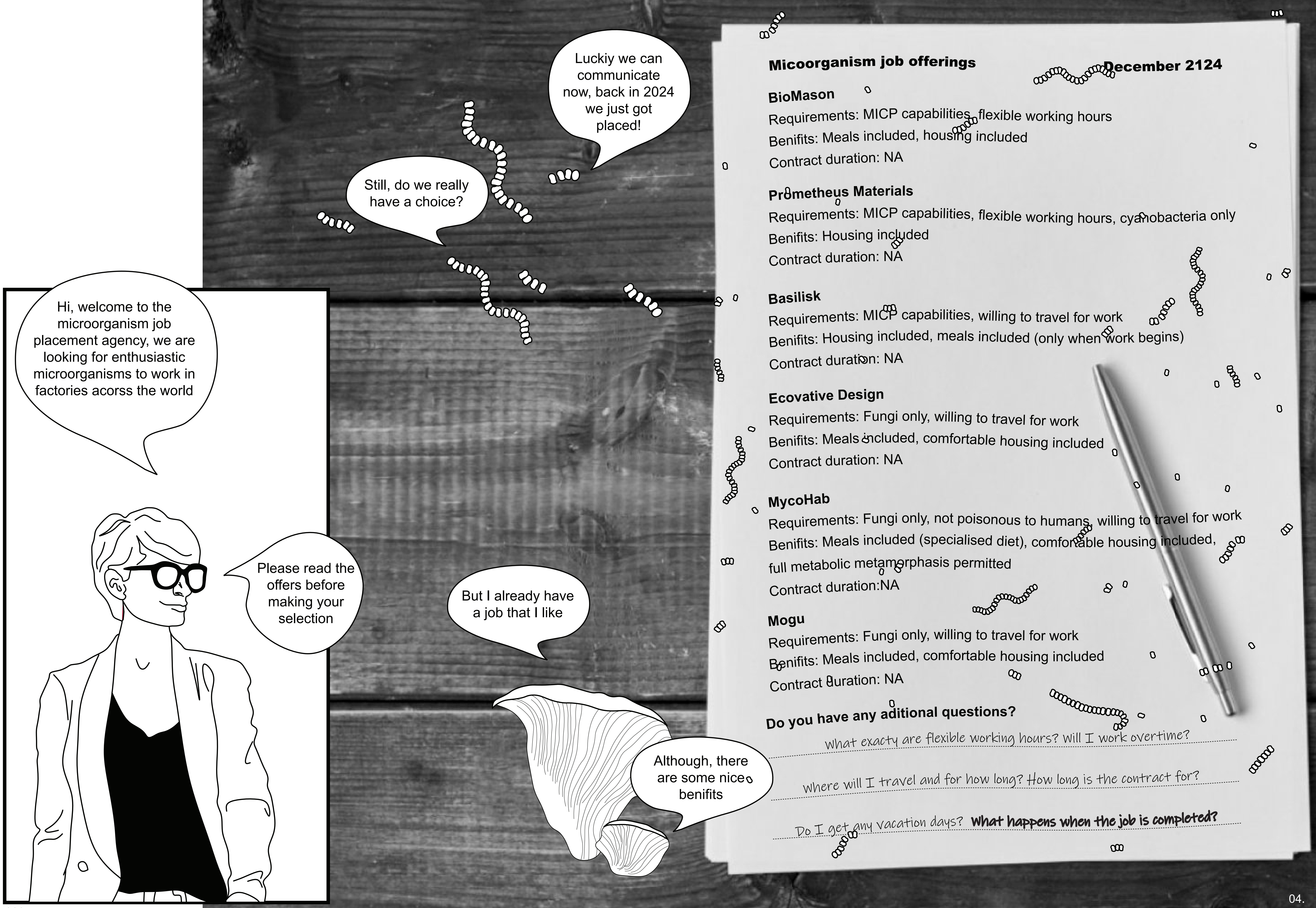
Figure 03. *Microorganism as resource - The mushroom unheard:* harvesting from existing ecosystem. Drawn by author, 2024

Figure 04. *Microorganism as labour - Agency through choice:* working terms and conditions and microbial agency. Drawn by author, 2024

Figure 05. *Microorganism as labour - You work while I wait:* the labour unseen is unrecognised. Drawn by author, 2024

Figure 06. *Microorganism as designer - The ownership of ideas:* unrecognised intelligence of microbial communities. Drawn by author, 2024


Great, now I have collected all the resources I need to make my environmentally friendly MycoComposite materials at home
Wait! Where are you taking me? I have an ecosystem to take care of!
How can we harvest resources sustainably while acknowledging the intricate ecosystems they are a part of?



Micoorganism job offerings **December 2124**

BioMason
Requirements: MICP capabilities, flexible working hours
Benifits: Meals included, housing included
Contract duration: NA

Prometheus Materials
Requirements: MICP capabilities, flexible working hours, cyanobacteria only
Benifits: Housing included
Contract duration: NA

Basilisk
Requirements: MICP capabilities, willing to travel for work
Benifits: Housing included, meals included (only when work begins)
Contract duration: NA

Ecovative Design
Requirements: Fungi only, willing to travel for work
Benifits: Meals included, comfortable housing included
Contract duration: NA

MycoHab
Requirements: Fungi only, not poisonous to humans, willing to travel for work
Benifits: Meals included (specialised diet), comfortable housing included, full metabolic metamorphasis permitted
Contract duration:NA

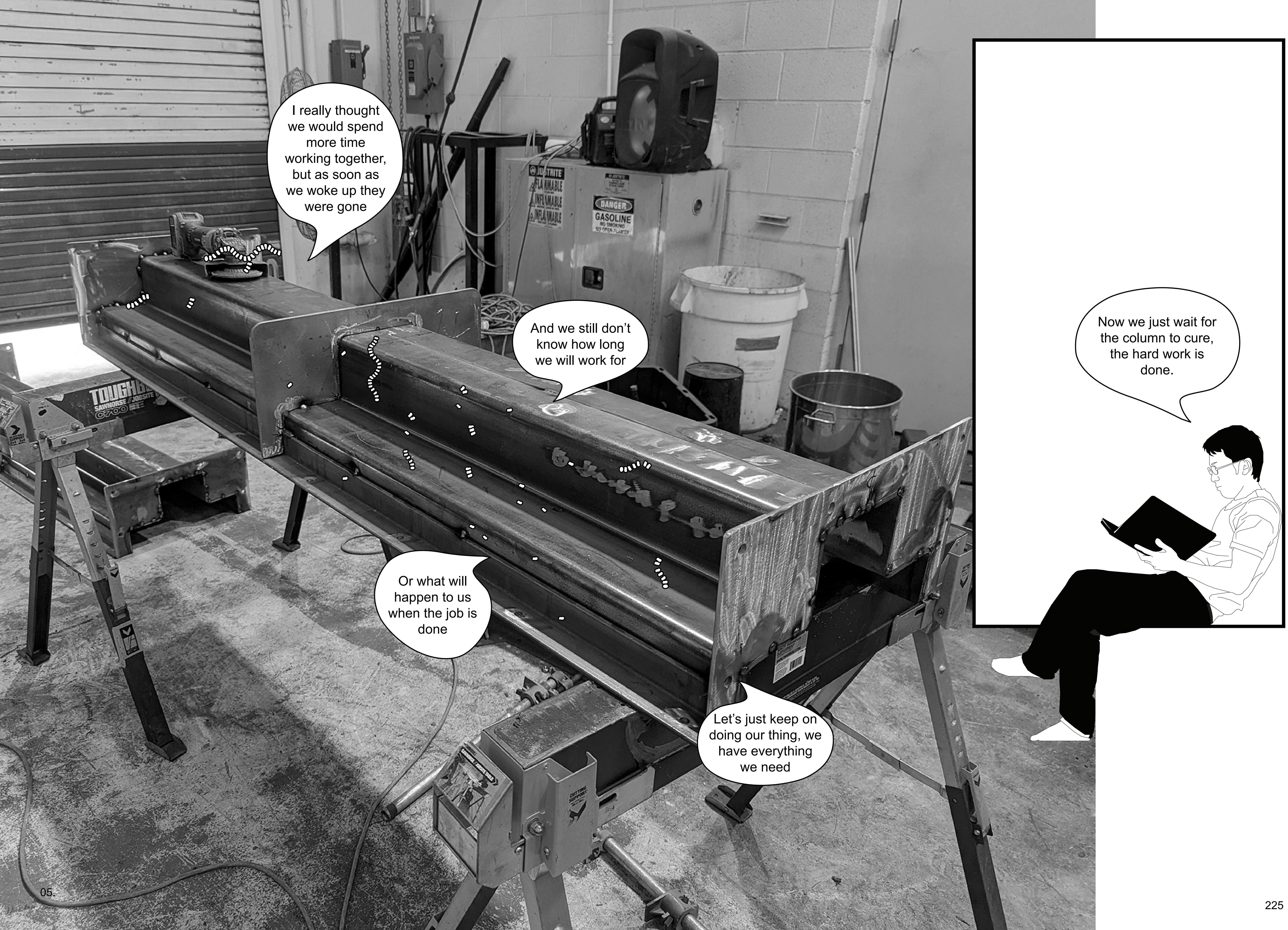
Mogu
Requirements: Fungi only, willing to travel for work
Benifits: Meals included, comfortable housing included
Contract duration: NA

Do you have any aditional questions?

What exacty are flexible working hours? Will I work overtime?

Where will I travel and for how long? How long is the contract for?

Do I get any vacation days? **What happens when the job is completed?**


I really thought we would spend more time working together, but as soon as we woke up they were gone
And we still don't know how long we will work for
Or what will happen to us when the job is done
Let's just keep on doing our thing, we have everything we need
Now we just wait for the column to cure, the hard work is done.


After all of these years, we have finally figured out how to decompose these new materials entering the ecosystem! Thank you all for working so hard together.
Wow, what an innovative idea to grow building materials with microorganisms and waste products, I think you will be up for an award.
Thank you, we have been working very hard on this development
Yes, we have really achieved something!
I just hope it's not too long before the next thing we need to adapt to

4.2. **A path forward**

As illustrated throughout the body of work, biocement and mycelium composites offer promising advantages as alternatives to conventional construction materials. On top of showcasing comparable, or even enhanced, material properties, these materials also offer major environmental benefits regarding resource depletion, end-of-life scenarios, energy requirements and carbon emissions, and position themselves attractively within a context of growing climate urgency and awareness of the impact of the construction industry. These materials are also changing architectural and design language and fostering important conversations regarding more-than-human collaborations and ethics hopefully working towards a more sustainable future.

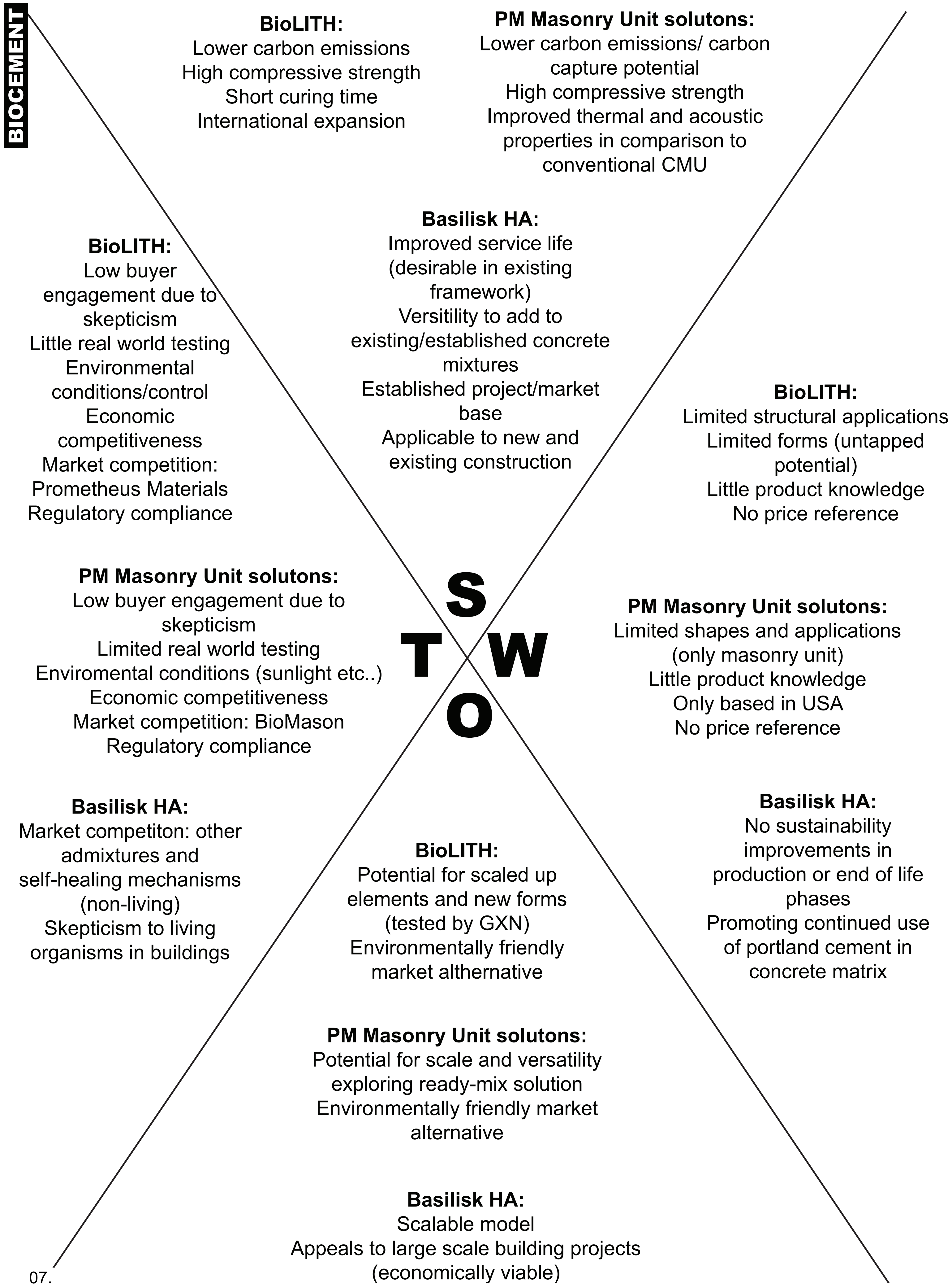
So, why are these materials then not commonly integrated into architectural practice?

The question of why these materials are not yet mainstream draws us to the limitations and challenges facing the widespread integration and scalability of these materials. In this section, these challenges will be identified and addressed, and a path forward considering a multi-dimensional approach based on the shifting paradigms they inspire will be explored.

4.2.1. A path forward: **Identifying the challenges**

Each material faces specific challenges limiting their integration into architectural practice. Here, through a SWOT analysis, the specific strengths, weaknesses, opportunities and threats of each product will be assessed in order to obtain an understanding of the challenges facing biocement and mycelium composites as a whole in order to imagine a path forward in a three-dimensional context.

Figure 07. *Biocement product SWOT analysis*



BioLITH:
Lower carbon emissions
High compressive strength
Short curing time
International expansion

PM Masonry Unit solutons:
Lower carbon emissions/ carbon capture potential
High compressive strength
Improved thermal and acoustic properties in comparison to conventional CMU

Basilisk HA:
Improved service life (desirable in existing framework)
Versitility to add to existing/established concrete mixtures
Established project/market base
Applicable to new and existing construction

BioLITH:
Low buyer engagement due to skepticism
Little real world testing
Environmental conditions/control
Economic competitiveness
Market competition: Prometheus Materials
Regulatory compliance

PM Masonry Unit solutons:
Low buyer engagement due to skepticism
Limited real world testing
Enviromental conditions (sunlight etc..)
Economic competitiveness
Market competition: BioMason
Regulatory compliance

Basilisk HA:
Market competiton: other admixtures and self-healing mechanisms (non-living)
Skepticism to living organisms in buildings

BioLITH:
Limited structural applications
Limited forms (untapped potential)
Little product knowledge
No price reference

PM Masonry Unit solutons:
Limited shapes and applications (only masonry unit)
Little product knowledge
Only based in USA
No price reference

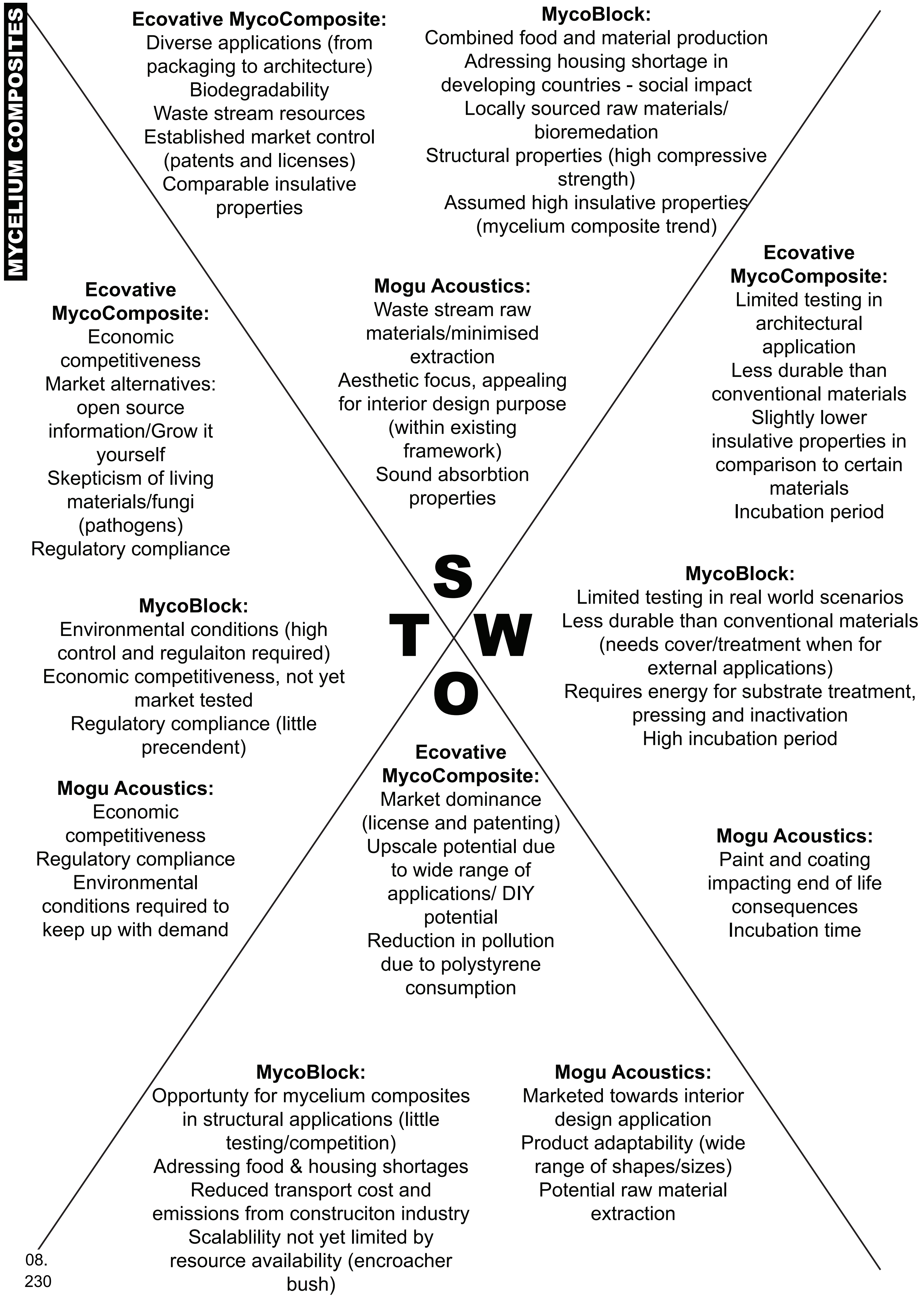
Basilisk HA:
No sustainability improvements in production or end of life phases
Promoting continued use of portland cement in concrete matrix

BioLITH:
Potential for scaled up elements and new forms (tested by GXN)
Environmentally friendly market althernative

PM Masonry Unit solutons:
Potential for scale and versatility exploring ready-mix solution
Environmentally friendly market alternative

Basilisk HA:
Scalable model
Appeals to large scale building projects (economically viable)

07.



Ecovative MycoComposite:
Diverse applications (from packaging to architecture)
Biodegradability
Waste stream resources
Established market control (patents and licenses)
Comparable insulative properties

MycoBlock:
Combined food and material production
Adressing housing shortage in developing countries - social impact
Locally sourced raw materials/ bioremedation
Structural properties (high compressive strength)
Assumed high insulative properties (mycelium composite trend)

Mogu Acoustics:
Waste stream raw materials/minimised extraction
Aesthetic focus, appealing for interior design purpose (within existing framework)
Sound absorbtion properties

Ecovative MycoComposite:
Limited testing in architectural application
Less durable than conventional materials
Slightly lower insulative properties in comparison to certain materials
Incubation period

MycoBlock:
Limited testing in real world scenarios
Less durable than conventional materials (needs cover/treatment when for external applications)
Requires energy for substrate treatment, pressing and inactivation
High incubation period

Mogu Acoustics:
Paint and coating impacting end of life consequences
Incubation time

Ecovative MycoComposite:
Market dominance (license and patenting)
Upscale potential due to wide range of applications/ DIY potential
Reduction in pollution due to polystyrene consumption

MycoBlock:
Opportunty for mycelium composites in structural applications (little testing/competition)
Adressing food & housing shortages
Reduced transport cost and emissions from construciton industry
Scalablility not yet limited by resource availability (encroacher bush)

Mogu Acoustics:
Marketed towards interior design application
Product adaptability (wide range of shapes/sizes)
Potential raw material extraction

Ecovative MycoComposite:
Economic competitiveness
Market alternatives: open source information/Grow it yourself
Skepticism of living materials/fungi (pathogens)
Regulatory compliance

MycoBlock:
Environmental conditions (high control and regulaiton required)
Economic competitiveness, not yet market tested
Regulatory compliance (little precendent)

Mogu Acoustics:
Economic competitiveness
Regulatory compliance
Environmental conditions required to keep up with demand

Figure 08. *Mycelium composite product SWOT analysis*

Based on the SWOT analysis[34] of each specific biocement and mycelium composite product along with consideration of production process, material properties, environmental impact and the contextual framework, the following limitations can be identified for the scalability of biocement and mycelium composite materials:

1. **Research and product development**
2. **Controlling environments (biological sensitivity)**
3. **Regulation and building codes**
4. **Market presence / product understanding**
5. **Economic Competitiveness**

So, what do these limitations mean and how can they be addressed in the practical, ethical and environmentally sustainable upscaling and integration of biocement and mycelium composites as construction materials?

[34] See figures 07 & 08: *SWOT analysis of biocement and mycelium composite products - page 229-230*

4.2.2. A path forward: **Research and product development**

Key words: *Barrier, ownership, process, applications, scale*

Challanges facing the wide scale implementation of biocement and mycelium composites begin with research and development. As evident through the products studied on the market, product development within the construction industry has been limited to a small range of singular elements such as tiles and masonry units in the case of biocement, and packaging, small-scale masonry builds and interior acoustic elements in the case of mycelium composites. Regarding this, there are two main factors to address, namely:

A: Product Diversity
B: Product Types

Product Types

It can be noted that the products available, particularly in the category of biocement are, themselves, small in scale with limited scalability. BioMason and Prometheus Materials have focused development, to this stage, on small elements such as tiles and masonry unit solutions. While these product types are important in the research and development process, as well as growing public awareness and acceptance of new materials, they miss out on important opportunities and properties offered by conventional materials such as concrete. One of the main draws of concrete is its adaptability and ability to be cast into a wide range of forms, supporting long spans and a specific architectural language come to be common practice. Limiting development of biocement to masonry construction elements makes it more comparable to well established elements like bricks or concrete masonry units. While this may enable a more environmentally friendly alternative to be able to partially, or fully, replace standard elements, particularly concrete masonry units, it limits the potential of the material in terms of scale, freedom in form and the potential to extend design imaginations.

BioMason, in particular, only showcases a singular product, a tile with no structural properties. The tile is only for decorative applications, a market which is already saturated with competing materials and producers. The company has however expanded from this by working in collaboration with Danish architecture and research firm GXN to develop and test the material in a larger scale element. This project is influential in proving the viability of bioconcrete as a more competitive alternative to conventional concrete and supporting its potential for scalability. This is, however, an area that requires much more attention in order to become fully implemented.

Prometheus Materials is taking a different approach to the scaling of biocement, showcasing a range of different forms and elements being developed using their method and technology, however the only available product to date is still a masonry unit solution. Of the planned developments, the most notable in showcasing the potential for major upscale and widespread integration is a proposed bioconcrete ready-mix. There is limited information on this product as it is still in development, but the company has mentioned that they have prototyped this product to a wall measuring 15 cm wide, 45 cm high and 1.2 m long, with a targeted compressive strength 20 – 31 MPa and a global warming potential of 0 $kgCO_2eq$ (Prometheus Materials, n.d.). While it is not commented on as to whether the company has yet been successful in the development of this product, its implementation could hold great potential for the scalability of biocement, enabling it to be used for a wider range of applications and forms, thereby making it more competitive in light of the advantages conventional concrete.

Mycelium composite materials are offered in a wide range of shapes for a diverse range of applications across fields. Regarding mycelium composite materials as an alternative to insulation such as EPS, the limitations in product range and focus are less of a concern than for biocement. However, testing mycelium

09.

Figure 09. *Exploring cohabitation imaginaries inspired by natural forms of biomineralisation:* Drawing by author, 2024

composite materials in in-place scenarios is an area that requires more investment in the research and development phase to test scalability.

By focusing on product types that are more adaptable, workable and versatile, both biocement and mycelium composite materials can be better positioned to replace concrete from an environmental perspective and enable and encourage design imaginaries in collaboration with nature.

Product Diversity

The development of product diversity through collaborative practices can also help explore applications beyond conventional units to allow the space for new materials to inform new, more sustainable and collaborative building typologies.

Mycelium composite materials can be noted to have a wider range of products being developed. This could be accredited to the different approaches to information sharing between the fields of biocement mycelium composite production. Information on the process of mycelium composite production is much more easily accessible, from open-source tutorial videos to grow it yourself (GIY) kits[35]. This enables a more organic and therefore more diverse base of research to develop across a wide range of applications, removing to some extent a harsh barrier between research and implementation. Ecovative Design is a pioneer in this field, establishing themselves and the material on the strong basis of their own research and development, to be able to share information to grow the field and diversity of products.

The companies producing biocement have a different approach to research and development, with three separate academic establishments driving the specific products. While this leads to more targeted research and results in a smaller product range, these companies have been able to acquire large sums of funding, greater exposure and credibility through associations

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See product: Grow-bio *GIY Kit*
Ecovative Design
Page 118-119

with academic institutions and accreditation by building standards. This however does not mean that mycelium composite materials have lower credibility, but rather a more organic and approachable interface to the general public, and each approach has its own strengths and weaknesses.

Through a more-than-human lens, could we extend the co-production of knowledge and diversity of outputs to include non-human entities? It is not only us humans who have the capacity to design and organise. Take natural biomineralisation in the form of coral and seashells for example. These natural systems are often described by biocement producers, including both BioMason and Prometheus materials, to be sources of inspiration for their technologies. However, this inspiration is limited to the process of biomineralisation, backgrounding the agency of corals, algae and mollusks to design and construct their habitats and broader ecosystems which also happen to vital protectors of the oceans.

Corals, through a symbiotic relationship with microalgae, partake in their own biomineralisation process with sea water to build complex, three-dimensional reef structures over time. These reefs not only serve as homeplaces for the coral and microalgae themselves, and a vast diversity of marine species, but also provide coastal protection. Similarly, mollusks, such as oysters, mussels, and snails, secrete calcium carbonate to build protective shells, creating on the go housing.

If we extend the conception of biomimicry, as a technology of nature embracing inspiration rather than pure mimicry (Fisch, 2017) and working in collaboration with nature, to the types of habitats that can be constructed through biomineralisation, the possibilities for biofabricated materials could be expanded beyond the scope of ‘mimicry’ of conventional building materials. At the same time, new typologies and design approaches that take the environment into account could be incorporated through collaborative design processes.

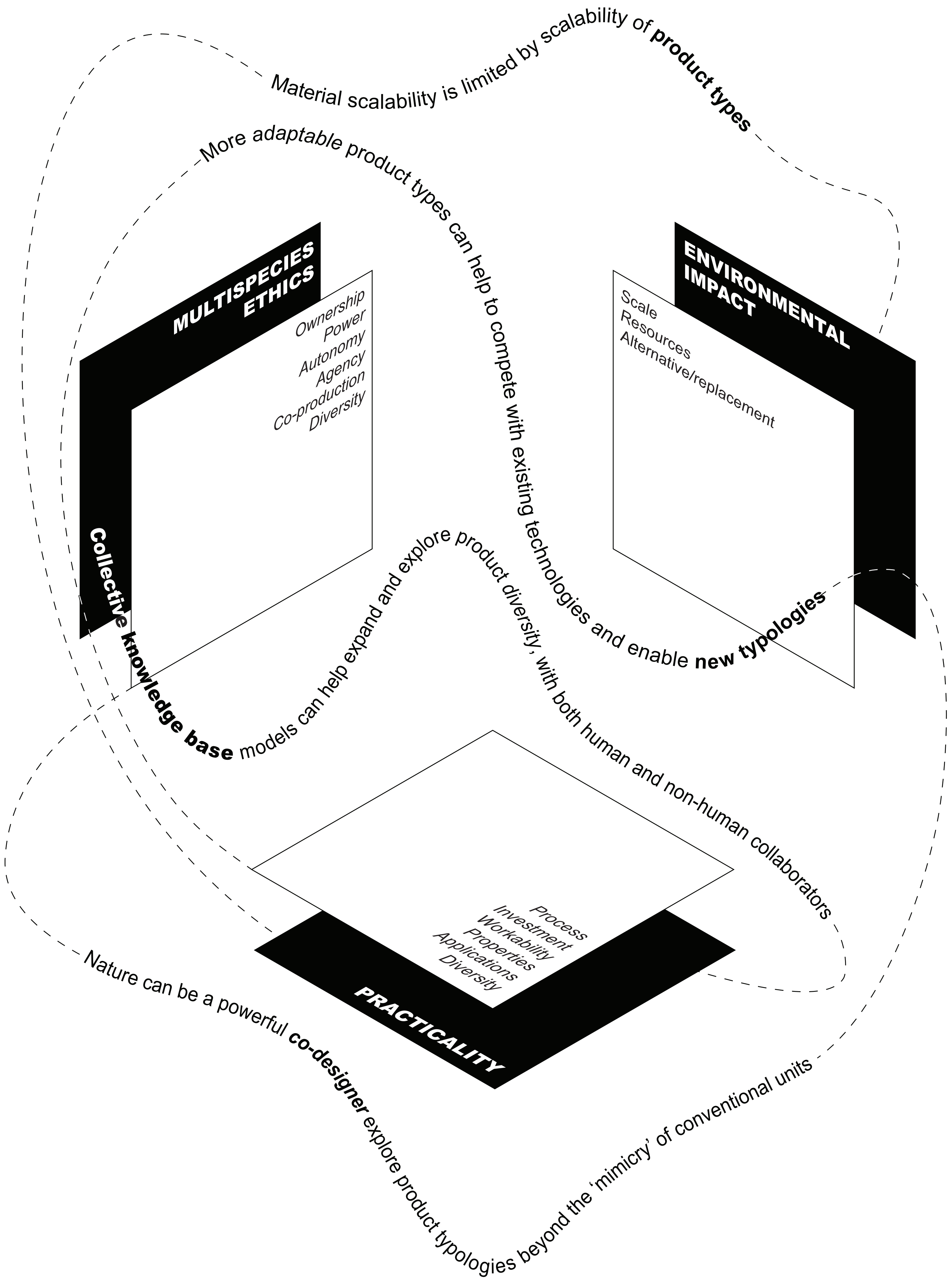

Figure 10. *Connecting the three dimensions considering research and product development*

10.

4.2.3. **A path forward: Controlling environments**

Key words: *Autonomy, agency, control, synthetic, environment, local, scale*

Addressing the scalability of biocement and mycelium composite materials brings up the volatility, complexity and environmental sensitivity of working with living organisms. Like with farming practices, environmental conditions need to be controlled by creating synthetic replications of ideal growth environments locally. However, in this process, some degree of control needs to be relinquished to locality, environmental unpredictability and the agency of the microorganisms themselves. Humans can only do so much to control environments, however natural conditions are sometimes out of the realm of control, particularly when scaling up production. For more collaborative interactions, we can consider adapting our actions and responding design decisions to environmental conditions, as microorganisms too can adapt to their environments.

Considering a global scaling of biocement and mycelium composite materials which require specific conditions for optimal growth, different locations will pose different challenges. A locality with a naturally humid climate will be more suited to mycelial growth than one that is very dry, therefore requiring less meddling with conditions, and lower energy requirements. Similarly, attempting to incorporate mycelium and bacterial growth processes into extremely cold climates will involve a higher degree of intervention in temperature control, even if growth conditions are considered 'ambient' in moderate climates, and therefore higher energy demands. This is reminiscent of Banham's Environmental Bubble, creating a distinct barrier between inside and outside conditions. Locality, in this way, impacts both the ease and environmental impacts of scaling and controlling conditions, and needs to be taken into account when considering if a material is an appropriate solution to its context.

Unlike the quest for control over environmental conditions evident in the production of biocement and mycelium composites, both the function and metabolisms of the living microalgae of ecoLogicStudio's Urban Algae Folly[36] are actively influenced by changing environmental conditions. When there is more sunlight, algae photosynthesise, and thereby the canopy provides more shade. Similarly, through digital regulation systems as a means of connection rather than a barrier, human visitors are able to stimulate the growth of the algae. While conditions and relationships are not as straightforward in material growth within a competitive market, there are lessons to be learned through recognising ways that both organisms, human and non-human, and architectural form can be influenced by and adapt to changing environments.

With this in mind, how can the limitations of scalability and incorporation of biocement and mycelium composite materials due to biological sensitivity to changing environmental conditions be addressed? While it is the nature of growth, globalisation and commercialisation of a product to be able to produce a standardised product in any locality to constantly meet demand, it is not the nature of nature. Fitting a product into this framework poses many challenges that need to be addressed gradually with a sense of adaptability.

Technically, owing to environmental control technologies, biocement and mycelium composite materials could be produced in any environment, however, from an environmental perspective, while they are generally considered as environmentally friendly construction materials in many ways, the benefits may not be the same in all environments. It is worth considering whether the challenged faced in environmental control, biological sensitivity and the associated extra investment, energy and resource demands make a material suitable for a specific location and expectations of scalability established by extractive material practices.

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See case study: *Urban Algae Folly*
ecoLogicStudio
Page 64-67

If not, we can return to a sense of adaptability and engage symbiotically with testing and research to develop new relationships with other organisms that may be more suited to different conditions. Here again, we can also look back to microorganisms as teachers and reflect on how we interact with our environment. By recognising ecosystems, including ecosystems of design and production, through complexity, ambiguity and unpredictability, we open ourselves, like microorganisms, to be open to adapting to conditions out of our control.

This sense of adaptability is critical in the practical, ethical and environmentally friendly integration of novel materials into existing frameworks, as well as in adressing our conceptions of growth and scalability for a sustianable future. We may need to bring further adaptability to these conceptions truly integrate new materials from a three-dimensional perspective.

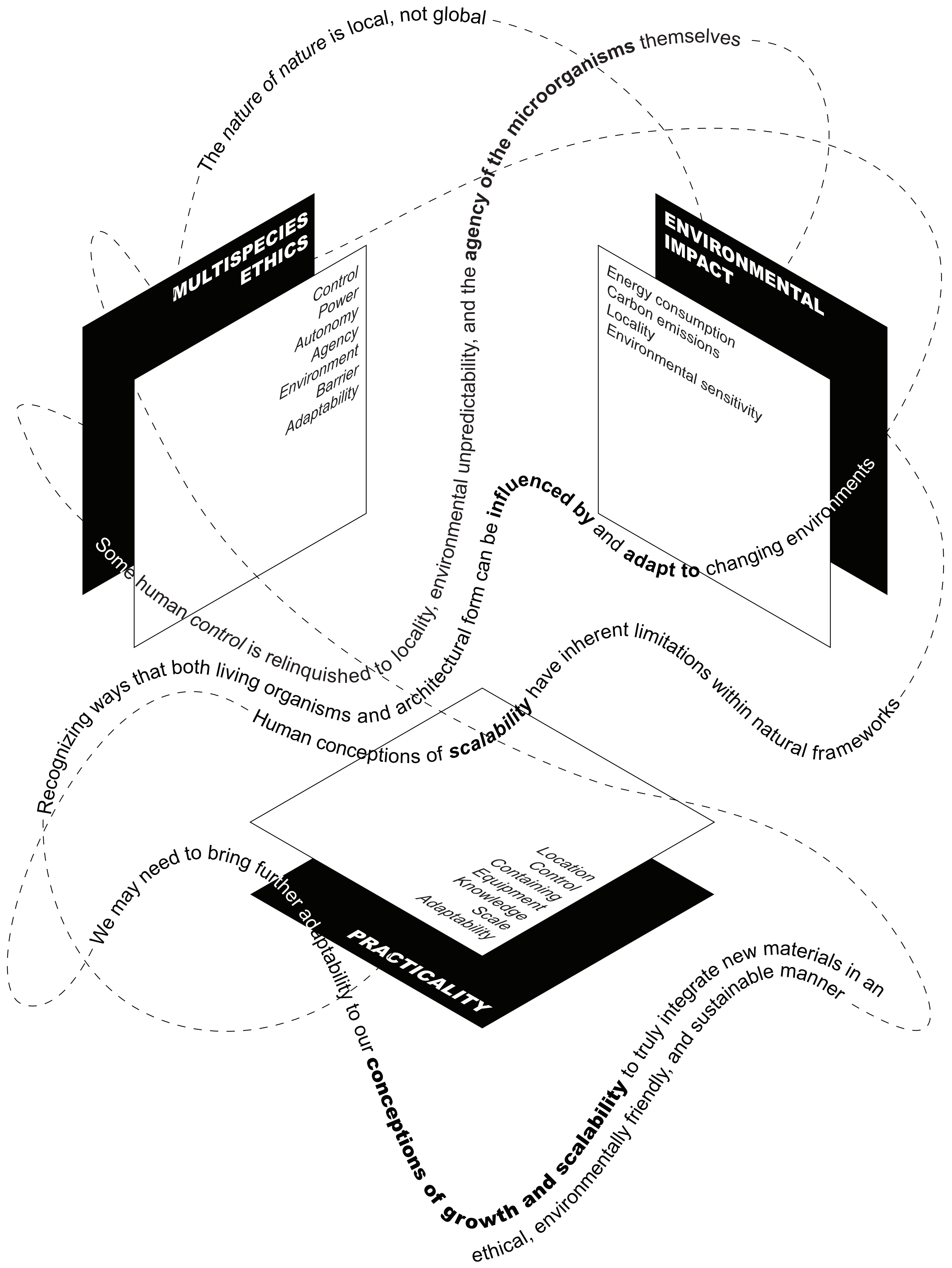


Figure 11. *Connecting the three dimensions considering environmental control*

11.

4.2.4. A path forward: **Regulations and Standardisation**

Key words: *Organising, control, complexity, process, scale*

Integrating novel materials into existing frameworks poses challenges at a regulatory level, making products difficult to test, approve and integrate into practice at a large scale.

Regulation selection

It has become evident through a technical comparison outlining applications and establishing comparative matrixes with existing construction materials that, that biocement and mycelium composite materials are not limited to one specific material comparison respectively within an existing framework. Even within each material category, be it biocement or mycelium composites, the product outcomes vary in terms of their potential applications within the construction industry. This poses challenges when attempting to assess materials in relation to existing standards and regulations, as there is not yet a recognised and comprehensive standard that encompasses the intricacies and complexities of biomaterials for construction.

Take mycelium composites for insulation as an example. While mycelium composites are competitive with expanded polystyrene (EPS) insulation for their thermal conductivity and insulative properties, there is reluctance towards their use due to their biodegradability. Their durability is often questioned because of this, and concerns arise therefore for their shelf-life in structure. This is a factor that is not understood, and not included in regulation for insulation materials.

Similarly, the development of standards and regulations for biomaterials need to be carefully considered and refrained from generalisations, as, like the world of microorganisms is so vast and varied, the material variations within each category are similarly diverse. For example, the regulations for mycelium composites could, as a generalisation, be drafted from that of insulation materials for instance. However, where then would materials like MycoHAB's MycoBlocks fit into the equation? They are both structural and insulative and require therefore a framework that is different from both standard insulation and structural regulations.

Universal experience

In the same vein, regulations for the inclusion of life or living building materials into building materials are under-developed. This is an area that is still approached with great uncertainty and scepticism. More recent projects including ecoLogicStudio's *Urban Algae Folly*, Neri Oxman's *Silk Pavilions* and Bento and Vinciane Despret's *In Vivo* project explore different avenues of living materials. A growing body of literature, including that of the In Vivo catalogue[37], explores the experience of living with these types of materials, highlighting, as noted by Bento and Despret, that "living with fungi is not a universal experience" (Despret, Aventin, Salme, & Bento, 2023, p. 306). While this observation refers to mycelium composite materials in particular, the premise can be relevant for all types of interspecies cohabitation in this sense and highlights the complexity of regulating and standardising living material integration. In an essay in *Human and Nature: a Partnership* entitled "An Unexpected Rapport: Mushrooms, a Designer + Everyone Else", Avery Shaw draws attention to how working with growing mushrooms shifted her approach as a designer, and how the mushrooms influenced her actions and environment as much as she tried to control theirs, and therefore she adapted naturally to their conditions (Shaw, 2019). This account also highlights the importance of adaptability, and the recognition of the agency of microorganisms as active players in the production process.

Learning from this premise, the development of regulations and guidelines for specific materials and living materials in general needs to encompass a sense of adaptability, in both specific application scenarios, and within the principles of architectural

[37] See case study: *In Vivo*
Bento & Vinciane Despret
Page 68-75

practice in general. We may need to adapt our actions and approaches to accommodate the inclusion of non-human life into building practice in relation to how we establish frameworks and regulations moving away from universalised approaches toward inclusion and adaptability in regulation for specific cases and modes of interaction. It might not in the beginning be an easy fit, but adapting to our surroundings, and maybe even thereby changing the ‘biologies’ (Landecker, 2016) or framework of architectural and construction practices and understanding, can work towards more seamless integration from both sides.

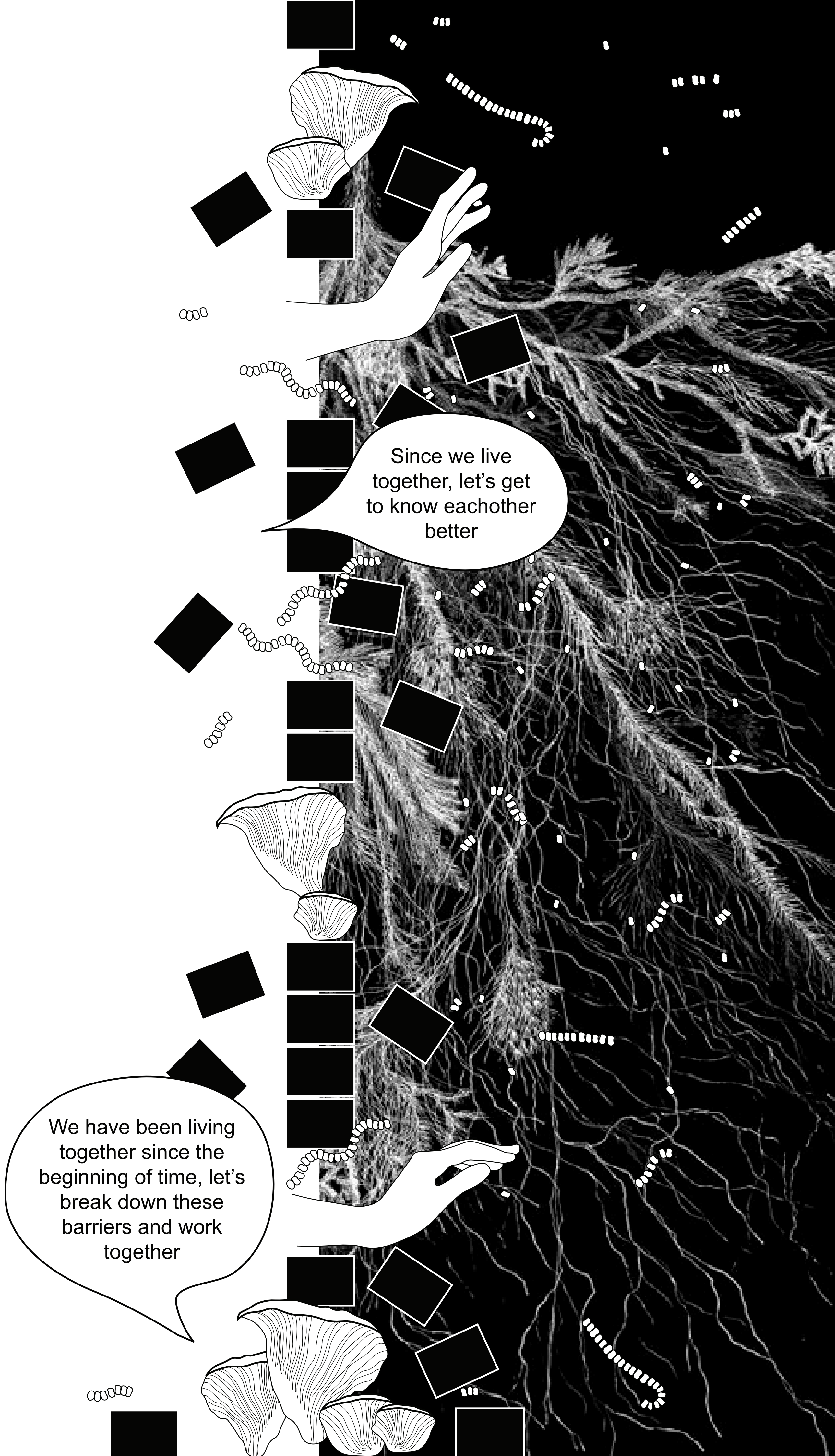


Figure 12. *Breaking down barriers:* living with living materials

12.

Time limitations / Delays

Practically, this uncertainty in the availability and type of regulatory framework available might limit the scalability of biocement and mycelium composite materials due to delays in testing and approving materials for integration. This can only be improved through an updating of frameworks mentioned above, but due to the complexity of the process, and multidisciplinary considerations that need to be considered, this will too be a long and tedious process. Therefore, to practically incorporate products into the existing context, the posibilities beyond the replacement of conventional materials in terms of application and exploration may be limited to theoretical and research-based projecting. Still, this type of work can increase exposure and demand for a revised set of guidelines to make these material explorations more inclusive at a larger scale.

Environmental assessment

While the marketing for biocement and mycelium composite materials is heavily based on the materials potential for being more environmentally conscious, there is little testing within the established sustainability grading framework to make these materials directly comparable and competitive to conventional materials. Therefore, although it sounds promising, the credibility of these materials may be minimised in this regard. However, current methods of assessing and grading sustainability are far from perfect and comprehensive, and themselves could benefit from taking a few lessons from microorganisms and the inclusion of a more-than-human approach.

Still, proving the benefits of biocement and mycelium composite materials by quantifying impact through Life Cycle Assessments (LCAs) and Environmental Product Declarations will make them directly comparable, and therefore more competitive within a market setting.

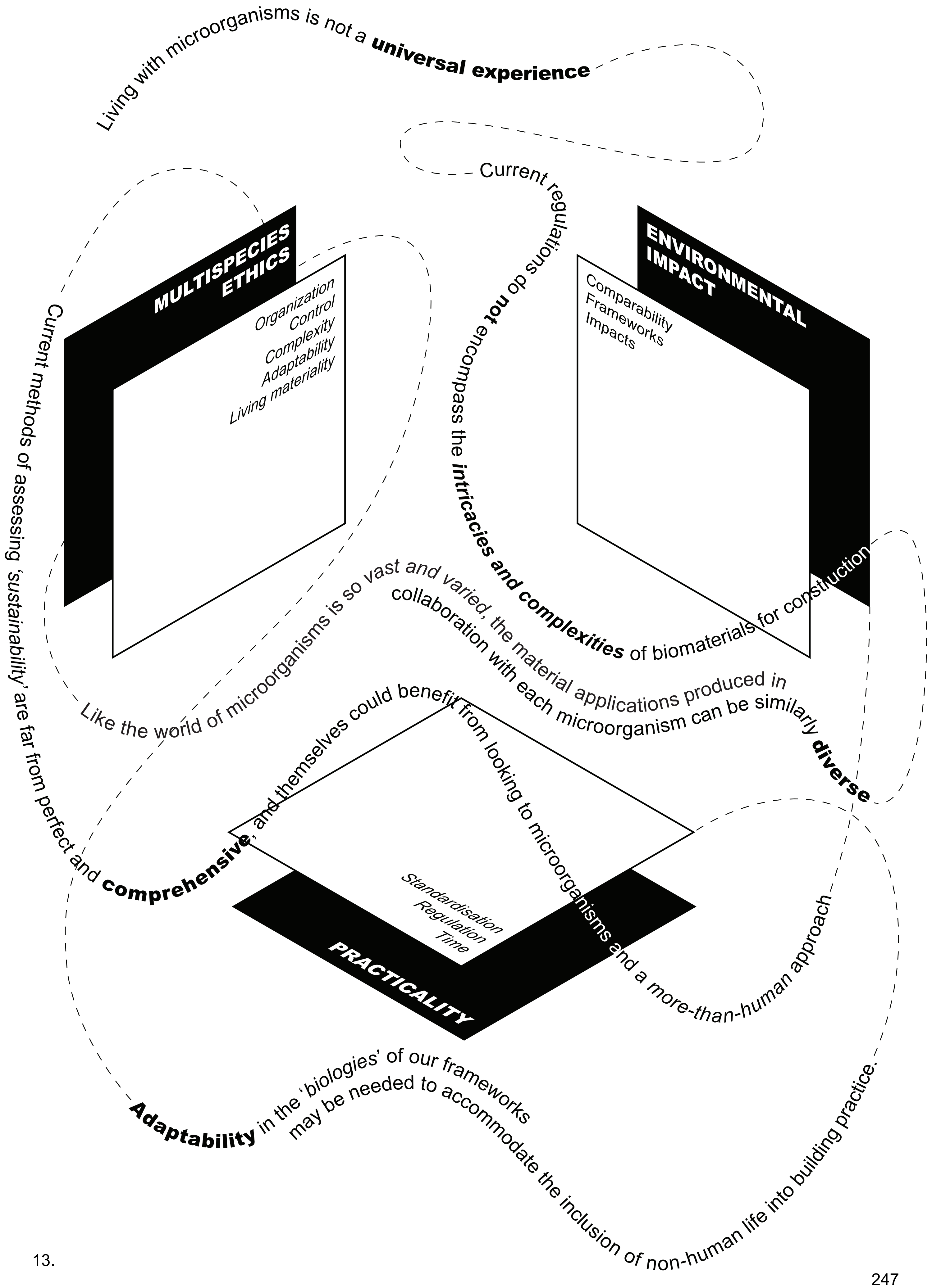


Figure 13. *Connecting the three dimensions considering regulations and standardisation*

4.2.5. **A path forward: Market presence & product understanding**

Key words: *Language, aesthetic, ownership, craftsmanship, environment, architect, designer, local, surrounding, process, power, scale*

Another limitation for biocement and mycelium materials is that they are not well known amongst potential users and the public in general and have different perceptions around the world. Limitations in this area are due to geopolitics, marketing and the way in which the products connect with potential users.

Geopolitics & availability

The majority of founding research for both mycelium composite materials and biocement started in the Unites States of America (USA). Pioneers in the field, including BioMason, Prometheus Materials and Ecovative Design, as well as the academic institutions supporting them are all geographically based in the USA. Therefore, the market monopoly and availability of these products for a long time was limited to this locality. Over time, the materials have expanded in their geographical scope to be produced and marketed globally, but the connections to the original founders have remained strong. In this way, US based companies have held on to the market monopoly, and ownership over intellectual property, yet are appealing to a wider audience and different market groups. These geopolitical dynamics influence the availability of products and knowledge and can limit or enable the scalability of novel materials.

For example, biocement research and production has expanded successfully to the European market, particularly in Denmark, by international collaborations with BioMason, while the methodology of Prometheus materials has remained geographically limited to the US. In 2021, BioMason partnered with IBF, Denmark's largest producer of precast concrete. Since then, they have been able to scale production, introducing the words first biocement factory, the Biobeten factory. This global expansion has also enabled collaborations to develop further research with companies including GXN, testing the viability of biocement at the scale of a precast column. BioMason has established a Danish subsidiary, Biomason Denmark ApS, supporting the expansion of the factory's production capabilities through research and testing and facilitating business development and partnerships within the European market. On top of this, BioMason's product is represented by FRONT Materials, previously Stone Cycling, promoting and advancing development of a collection of sustainable and aesthetic building materials. This type of representation helps promote and expand the reach of BioMason's products, with a focus on marketing, sustainability and aesthetics.

Basilisk, on the other hand, was developed and founded in the Netherlands, in collaboration with TU Delft. They too have expanded their global relations, currently involved in partnerships with distributors across Europe, Southern Asia, the Middle East, Australia and the Caribbean. Basilisk represents the largest global availability of biocement products.

Due to the geopolitics of the material and its production, biocement products, particularly in the form of complete elements, is limited to the American and European market. Outside of these regions, there is limited access to biocement as a product, and access to information to develop in southern areas of the globe is limited too. Africa and South America do not yet have access to any locally produced biocement product, and due to the highly patented and lab-driven nature of the biocement production process, would need to engage in partnerships with established companies, or endure high transport cost and emissions, in order to make products available to use in these parts of the world.

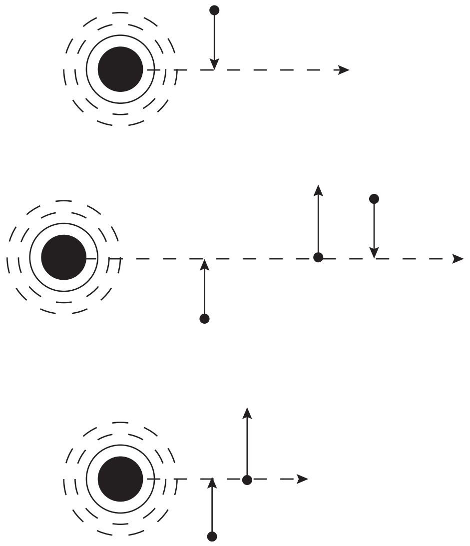
In contrast to this, the geographical expansion of mycelium composite materials follows a different narrative. Mycology is a field that has developed organically, led by self-proclaimed mushroom enthusiasts. Because of this, the sharing of information is more embedded in the field, and the popularisation of mycelium composite production has taken a more “do-it yourself” or “grow-it-yourself” nature, and as a result the reach and availability of mycelium composite materials extends to a broader geographical range.

Ecovative Design, a pioneer and stakeholder within mycelium product development, has developed a business model that taps into this potential in two ways. Firstly, Ecovative Design launched a spinoff called Grow.bio which focuses on Grow It Yourself or GIY kits containing all the necessary elements to grow mycelium composite materials at home. They also release educational videos and tutorials showing people how to make and experiment with all sorts of interesting creations using mycelium. Secondly, Ecovative Design has a large list of partnerships and an open patent program. In this way, they welcome others to build on their established ecosystem through open access to core composite patents, unrestricted use of patented techniques and zero-cost licensing for program participants. Through this model, Ecovative Design promotes cross-pollination of ideas within the mycelium community, building upon a shared knowledge base to accelerate research and development efforts (Ecovative Design, n.d.). This strategy allows for faster expansion, both through research and development and commercialisation of mycelium composite materials, enabling a global network of contributors to the field.

Due to this approach to information accessibility, mycelium composite materials, although still primarily developed in the US and EU, can be available globally. It is also possible to easily learn about, implement and adapt the production of mycelium composite materials regardless of locality.

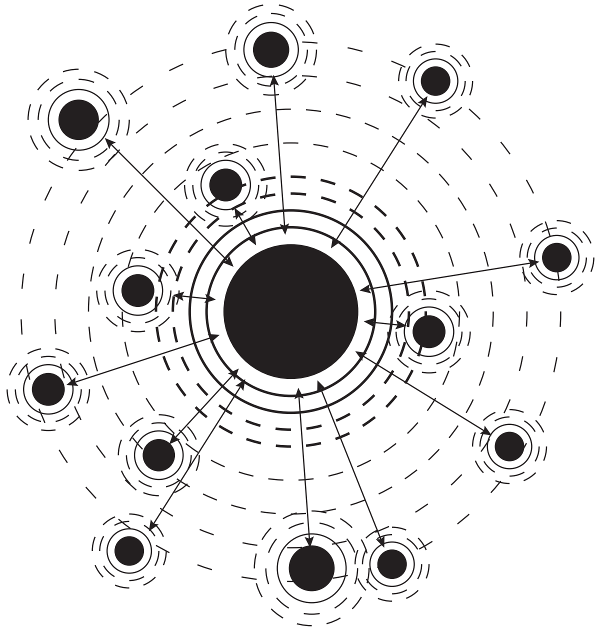
Taking these considerations into account, the rate and geography of the scalability of materials becomes intertwined with the conception of ownership. While ownership is often idealised as a symbol of power and control, it can also contribute to the formation of barriers, limiting growth through connections and relationships. When considering the future of biocement and mycelium composites, and their potential for scalability, dynamics of ownership and power need to be considered and addressed with recognition of their limiting capacities.

Is singular ownership a power or limitation?



14.

Figure 14. *Diagramatic representation of the growth of a competition for power over knowledge:* Diagram by author, 2024



15.

Figure 15. *Diagramatic representation of the growth of a collective knowledge base*: Diagram by author, 2024

Market gaps and strategies

While biocement and mycelium composites might not offer all of the same selling points that conventional materials such as concrete or insulation do, particularly in terms of wide scale availability, established trust and low cost, they have other attractive advantages that can help them gain traction within the construction material market. The story of biocement and mycelium composite draws parallels to the fast fashion industry in many ways. While cheap, trendy items may seem most appealing at first, there is merit paying a higher premium, or waiting a longer period of time for a higher quality product that is more ethical, now for humans and non-humans, and more environmentally friendly. With growing social and environmental unease, these elements are gaining awareness, and many people are choosing to shop more consciously. While this is not a direct comparison, and it is not to say that conventional materials are low quality products, but rather a comparison to emphasise the merit in quality, narrative and cultivating a specific language of consciousness.

Similarly, this draws parallels with the comparison of mass-production and craftsmanship. While mass production has held its popularity, there has historically always been a return to craftsmanship in some sense as a way to connect to ourselves and nature.

The transition from fast, cheap, mass-produced consumerism to more conscious, crafted consumerism is still in its infancy, and there is concern as to whether it is even possible at all in the light of our addiction to consumption and endless growth. Mass production and fast fashion still hold immense power, however, there is a market gap for materials such as biocement and mycelium composites within this framework, and with the right promotion to the right audience, there is potential for these materials to establish themselves.

Microbial scepticism

Since the microorganisms utilised for both mycelium composites and biocement have been proven completely safe and non-pathogenic, the scepticism towards living in such close contact with microorganisms stems from a fear of the unknown ‘other’. This is a concept that has been historically difficult to overcome, evident through narratives of health, food production and now construction materials.

The theme of fear of bacteria has been historically embedded in culture and architectural practice. Highlighted through the clean, unornamented aesthetic of modern architecture, excessive cleaning and turning the home into a hospital we are now realising may be the root cause of a plethora of new illnesses. Through this making of barriers between human and bacteria aided by architecture, we have lost what we now know is a vital and blurred connection between the inside and outside worlds.

This concept is highlighted particularly when incorporating microorganisms and other living beings into building materials. Through this relation, we are actively bringing the other into our safe spaces, our buildings, which we have historically constructed to protect ourselves form the external world. However, this is an important challenge to face, both for the understanding of biocement and mycelium composites as building materials, and our own conceptions of health, buildings, self and other.
Recent literature and projects explore these relations, integrating a deeper understanding of the diversity and importance of microorganisms into the discourse of architectural and design practices. For example, Colomina and Wigley explore this relationship from an architectural perspective through their work including the essay entitled “The Bacterial Clients of Modern Architecture”. Through this perspective they explore how bacteria, in the form of disease, has historically been shaping the way we build, from explicitly opposing bacteria and using architecture as a mechanism to separate the human from the other, to the new “hygienic hypothesis”, identifying this segregation from bacteria

and controlling of environments as the root of new disorders associated with urban society (Colomina & Wigley, 2021).

Still, recent events such as COVID-19 have reinforced this idea of distancing, sanitation, sterility and antibiotic tendencies, which again we have realised over the long run are weakening our immune systems and developing stronger, anti-biotic resistant organisms.

Our relationship with bacteria is one filled with complexity. Even though we are beginning to understand our interconnected relationship, we still value health and naturally fight that which opposes it. We still struggle to distinguish between ‘good’ and ‘bad’ microorganisms, and through this further emphasise the barrier. However, it is evident that with growing knowledge and understanding, and testing relations over time, that we have opened ourselves up to explore the blurring of the strict boundaries between interior and exterior, good and bad and self and other through interactions with microorganisms, both in our bodies and buildings. We can hope, that through further exploration, proof and understanding, and by experiencing the materials firsthand, these barriers may become less and less prominent in our attitude towards microorganisms as a whole so that we can live in harmony with both built and natural environments.

Changing perceptions of beauty

This changing perception is also expressed in the new architecural aesthetic that microorganisms are helping to develop through their role in material production.

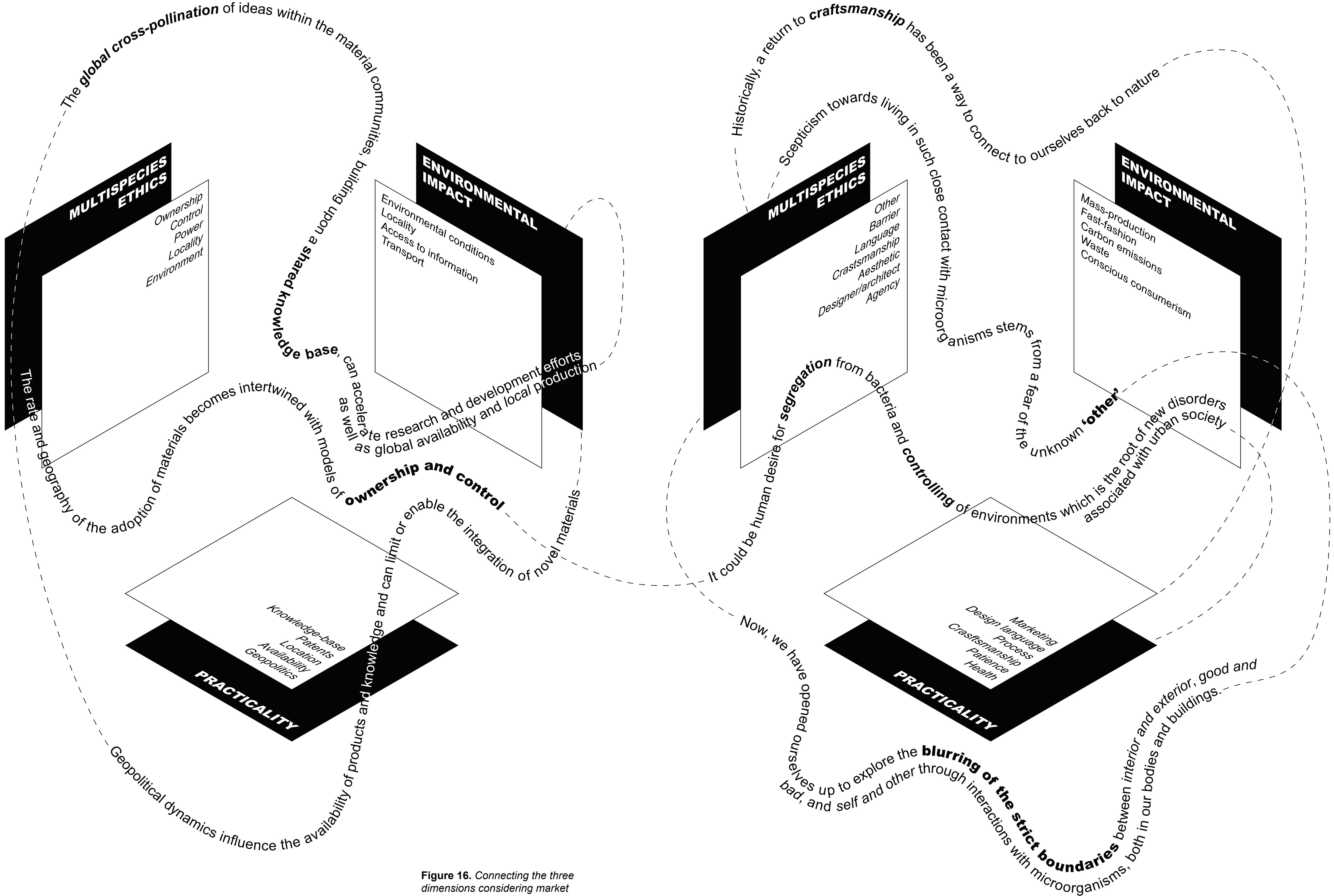
Aesthetics and architectural language can be a powerful tool in exposure, acceptance and popularisation of new materiality. As concrete, through its unique aesthetic and structural properties, created a completely new architectural language, further enhancing its popularity, biocement and mycelium composites have the potential to create a new architectural language through narrative and aesthetics, encouraging their integration and expanding imagination.

As Adrian Forty points out in *Concrete and Culture: A Material History* (2012), concrete embodies aesthetic dualities and paradoxes. It is a highly industrial material, yet it possesses expressive potential that has allowed architects to push aesthetic boundaries and challenge conceptions of beauty. Similarly, biocement and mycelium composites as construction materials offer their own aesthetic paradox. The materials themselves embody the complex paradoxes of shifting paradigms towards microbial interactions.

Biocement is simultaneously hard yet organic in its production. While replication of existing, regularised construction elements is currently common practice in biocement production, the biological roots and natural biomineralised structures are seeping their way into architectural inspiration, offering potential for exploring new forms and models of living.

Mycelium composites are simultaneously sterile, due to the control over their growth conditions, and alive at the same time. They express control over environments yet embody the agency of life to inspire imagination, texture and form.

As concrete’s paradoxes aided in its traction, the paradoxes of biomaterials give them great potential for impacting the aesthetics of the built environment. The multi-layered complexity of their processes, so closely related to the relations in our own bodies, inspires a new imagination for collaborative processes of production and the potential for a new architectural language.



The ***global cross-pollination*** of ideas within the material communities, building upon a **shared knowledge base**, can accelerate research and development efforts as well as global availability and *local production*

The rate and geography of the adoption of materials becomes intertwined with models of **ownership and control**

Geopolitical dynamics influence the availability of products and knowledge and can limit or enable the integration of novel materials

Historically, a return to ***craftsmanship*** has been a way to connect to ourselves back to nature

Scepticism towards living in such close contact with microorganisms stems from a fear of the unknown **‘other’**

It could be human desire for ***segregation*** from bacteria and **controlling** of environments which is the root of new disorders associated with urban society

Now, we have opened ourselves up to explore the **blurring of the strict boundaries** between *interior and exterior, good and bad*, and *self and other* through interactions with microorganisms, both in our bodies and buildings.

Figure 16. *Connecting the three dimensions considering market presence and product understanding*

16.

4.2.6. A path forward: economic competitiveness

Key words: *Scale, autonomy, resource, labour, control, power*

Since most of the products available on the market do not have listed prices, it is difficult to directly compare how much biocement and mycelium composite materials cost in comparison to conventional materials.

This in itself limits the use of the materials it is not accessible to compare them with conventional products. Therefore, due to their novelty, small scale production and limited availability, it is generally assumed that they will in fact be more expensive and therefore maybe not a viable option. Making cost information more publicly available might help spread knowledge of the products and enable potential users to practically consider them as alternatives.

Still, considering that biomaterials are probably more expensive than conventional materials, the following categories can be considered in overcoming limitations due to cost from a three-dimensional perspective:

1. Production establishment
2. Production time and stages

Production establishment

Since both biocement and mycelium composite materials are fairly novel, the infrastructure for their production is less established. The only known scaled production facility is BioMason's Biobeten factory in Denmark, which claims to be the world's first biocement factory. This facility was only very recently established, commissioned in 2023, showcasing how novel the scaled production of these materials is. In contrast to well established industries like concrete and cement, with streamlined production, this novelty in production facilities would most likely result in higher material prices.

Similarly, with new production processes, new equipment may need to be established and installed. BioMason has been careful in selecting the equipment for the factory, using existing industrial equipment found in paver and block factories, including a mixer and a press, which are adapted with feeding and curing systems to enable biocementation. This is an interesting proposal, as there are advantages and disadvantages in terms of cost to the production process. Utilising existing equipment means that initially the equipment will be less expensive, as it is already designed, and production is already established. Costs may however occur in the adaptation of existing machinery to facilitate biocementation but are expected to be less than designing specialised equipment. However, over the long term, if production does increase, the adapting of existing machinery in this manner may not be the most efficient for production, nor the most cost-effective option.

In short, if biocement and mycelium composites aim to be competitive with conventional products at a large scale, careful consideration will need to be given to the production facilities and equipment related with their production.

Production time and stages

The production time scale also contributes to the costs associated with material production.

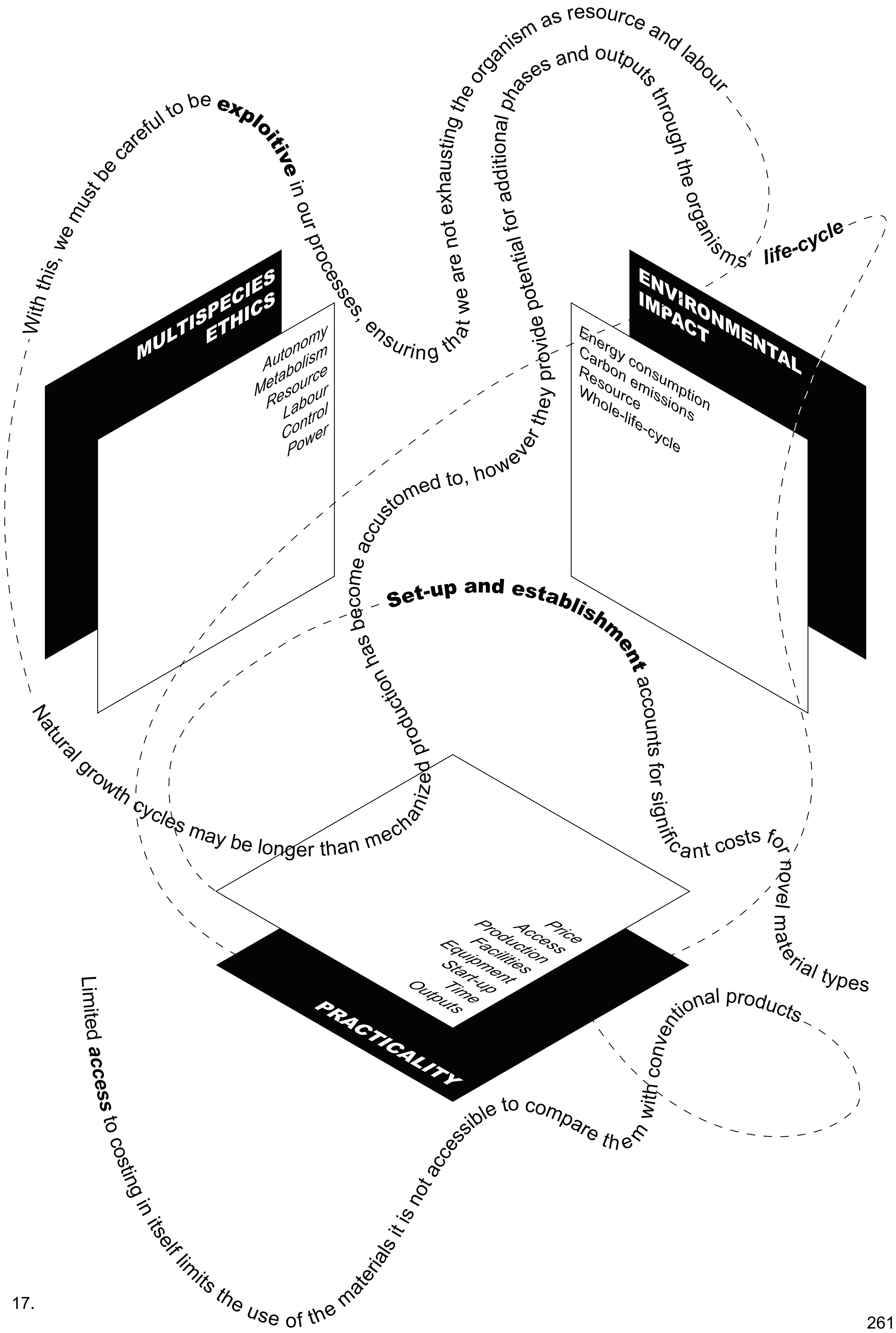
Biocement materials actually claim to have shorter production time, which should in theory contribute to quicker production and therefore lower costs, however there are other factors to consider in this equation. Apart from the other factors mentioned in this section, there is the time consideration of the materials being new and not yet efficiently established. Therefore, time still needs to be dedicated to back-and-forth research and testing to produce a finalised product.

Mycelium composites on the other hand are limited by their growth period. The time taken for the spores to fully bind a substrate can range anywhere from 5 to 14 days (Vélez, 2023, p. 101) before even beginning the inactivation process. In comparison, standard expanded polystyrene can be formed in a matter of minutes. However, there is potential in this department, as explored by MycoHAB, for an additional output from the growth process in the form of edible and nutritious fruiting bodies: mushrooms. This way of looking at it can justify the extended time period when reframing the outputs of the process as twofold. In this manner, the initial growth period is viewed as working towards the mushroom output, which can be sold for additional income or community upliftment. Then, the material production begins by using this free, waste resource as the starting point for material production, whereafter the process can happen on a daily basis.

The benefit of utilising microorganisms in material production is highlighted through nature's natural metabolic capacities which open up possibilities for exploring the whole-life cycle of the organism rather that isolating specific properties. With this, we must be careful to be exploitive in our processes, ensuring that we are not 'milking' the organism from all angles. On this, Neri Oxman commented that allowing an organism, in her case the silkworm[38], to undergo its full metamorphosis is in fact an ethical act as it moves away from rendering the organism an artificial object (Fisch, 2017, p. 21). On top of this, it is recognised that the quality of ethics itself should emerge within a system of relations rather than from a binding logic (Fisch, 2017, p. 22).

From this perspective, we must recognise that ethical considerations will differ from organism to organism, and process to process, but an understanding of the full metamorphosis can be beneficial both in ethics towards the organism itself and symbiotically the human agenda. Still, this is a conversation that needs to be approached with sensitivity as we cannot yet truly know the views of the organisms themselves.

[38] See case study: *Silk I & Silk II* Neri Oxman Page 46-53



17.

Figure 17. *Connecting the three dimensions considering economic competitiveness*

Conclusion

This research concludes in integrating all of the three identified dimensions of biocement and mycelium composites, as construction materials, to understand the shifting paradigms they inspire in architectural practice as a whole and pave a future for their scalability and integration in response to specific limitations. Each of the dimensions offered useful insight to formulate a more complex understanding to be able to respond to the research questions as holistically as possible considering a more-than-human perspective. This was not a linear process, and grappling with these concepts and bridging interdisciplinary information was even more complex than expected. However, ultimately, including multi-disciplinary and multi-species perspectives was useful to formulate a deeper understanding and more informed set of principles to propose a future for the integration and scalability of these materials.

Tracing the changing human nature relationship over historical narratives, using architectural case studies, set up a framework for theoretical understanding and the identification of key concepts to help achieve the final aim of a three-dimensional analysis. This historical narrative also helped to bridge disciplines, and prove that there is a connection between health, chemistry, biology and architecture through how we, as humans, have historically interacted with and positioned microorganisms in relation to ourselves. It was also shown, through case studies and publications, that this narrative is still shifting, and the way in which we understand the role of microorganisms and their relations to ourselves, and ecosystems, is becoming more interconnected as we understand it more. This shift in understanding is shaping our relationship with nature as a whole, and therefore manifesting in major paradigm shifts in architectural practice and theory.

This understanding set up a strong framework to include a third, more complex dimension of interspecies relations into architectural ethics. However, it can be even more useful when grounded in material examples.

The products selected were useful in showcasing the current state of fact of biocement and mycelium composites within an existing global framework of construction materials. However, as the products are relatively new, it was in some instances difficult to find data, either due to lack of adequate testing or publication of results. However, with the data obtained, it was possible to formulate a general understanding of each material and its properties, and it was proved, through a technical comparison of material properties, that these materials offer potential to be competitive alternatives with conventional materials.

Biocement products, as they currently stand, are comparable with masonry unit construction or paving, either clay bricks or concrete, but have the potential for further development in larger scale elements and ready-mix solutions. Basilisk has also proved that bacteria have the potential to improve the durability and service life of existing concrete types.

Mycelium composites, on the other hand, showcase their strength in their thermal and acoustic properties, making them viable alternatives to existing insulation materials, particularly expanded polystyrene (EPS) insulation. However, MycoHAB has proved with their MycoBlock that it is possible to achieve compressive strengths that enable mycelium composites to be a viable material for structural masonry construction.

The study of this range of products showcased that each material type has variation within it, and although there are clear properties for each that make them most suitable for specific applications, exploration has extended beyond this, showcasing the versatility of the capacity of the respective organisms for production.

While these materials showcase properties that highlight their viability for specific applications, they are still novel in their development and have a long way to go technically to truly compare with conventional materials in terms of product types, establishment and scale.

Establishing alternatives allowed for a more targeted environmental comparison, in which biocement and mycelium composites showcased a range of benefits. In this area too, due to the novelty of the materials, there was in some instances a lack of data, particularly in regard to specific carbon emissions, that made it difficult to accurately compare these materials with more established products. This is an area that I propose would be beneficial to invest time in researching and testing, in order to facilitate more accurate comparison.

Still, from available data, the main environmental benefits of each material can be understood. The main benefits of biocement lie in eliminating the need for limestone extraction and processing and related carbon emissions. While biologically generated limestone still requires development to fully replace conventional concrete, it proposes new opportunities and a promising path forward. Biocement, through self-healing, is also able to improve durability of existing concrete structures, reducing the need for maintenance and replacement, reducing material demand.

The benefits of mycelium composites, on the other hand, lie in its biodegradability, substantially minimising pollution and contribution to landfill mass typical of conventional EPS insulation. Mycelium composite materials, in theory, can disappear without a trace, helping reduce human impact on the planet. They also reduce resource consumption and carbon emissions and have the added benefit of being great thermal insulation materials, which helps reduce energy consumption due to heating and cooling of buildings.

The study of both of these material types also goes to show that there are many different approaches to sustainability, and it is not a one sise fits all solution. Similarly, biocement and mycelium composites are not a silver bullet to fix all environmental problems and excuse the construction industry from its problematic practices of rapid development. Even though these materials can be much lighter on the planets systems in specific areas than their conventional alternatives, the mass production of any specific material has the potential to interfere with natural systems. We do not yet know the implications of the mass use of specific resources, or quantities of materials left in the environment on the complex and intricate systems of the planet and must be careful with our tendency to meddle with nature.

Addressing biocement and mycelium composite materials from a technical and environmental perspective, and understanding the specific producers and their strategies, added further insight to the understanding of these materials in a broader context of interspecies ethics. It is only, therefore, in the overlaying of these three dimensions, that an understanding of the paradigm shifts they inspire and clearer future for sustainable integration can emerge.

The paradigm shifts identified encompass the ethical considerations that arose from the historical human-nature narrative and current uses of microorganisms in architectural materials and highlight how new ways of thinking fostered by interspecies collaboration can reshape architectural practice. The main paradigm shifts identified through this methodology include shifts in topics of sharing and ownership, aesthetics and language, and organisation and hierarchy.

The paradigm shifts in sharing and ownership address historically embedded tendencies of human control and believed ownership of the planet and its natural systems, as entities to be used and exploited. Collaborating with non-human beings, through material production, makes architects and engineers question their own agency, control and ownership of the production process, handing a large portion of the key labour, and design development to some extent, to non-human microorganisms. The interdisciplinary nature of the development and production of these types of materials also brings architecture and design into contact with alternative, more organic methodologies of growth and development that promote collective knowledge rather than the safe holding of information.

Biocement and mycelium composites, in this historical and theoretical context, also highlight shifts in aesthetics and language, addressing ethical concerns of microbial fear and scepticism, reinforcement of the microbial other, and the complexities of interspecies communication. As we form closer relationships and deeper understanding of the nature of microorganisms and their relations, paradigms in other disciplines including health, agriculture, food production and architecture are shifting in a probiotic direction, recognising that not all bacteria are enemies, but can actually be allies. This is fostering new architectural expressions and inspiring a sense of curiosity to know and understand the depth of the microbial world, which we now know to be inseparable from healthy ecosystems, including our own body.

The third ethical consideration relates to organisation and hierarchy, and the role of living, non-human actors in the production process. Critical to this exploration is the consideration of the capacity and implications of non-human agents within the roles of resource, labour and architect or designer. These categories, in a human context, define how agents are treated and compensated and can result in discriminatory or exploitive practices, as evident in our own practices with human and non-human beings. Working so closely with non-human beings, showcasing the capacity for each of these roles, invites a deeper exploration and appreciation of the agency of non-human life and can enable a sense of empathy, steering us away from exploitive practices and fostering a better approach to resource and labour.

It is recognised and identified that there are many limitations to scalability and widespread implementation of biocement and mycelium composite products within the construction industry.

In response to the main limitations identified, the application of this three-dimensional approach to biocement and mycelium composites inspired the following guidelines for practical, ethical and environmentally scaling and implementation:

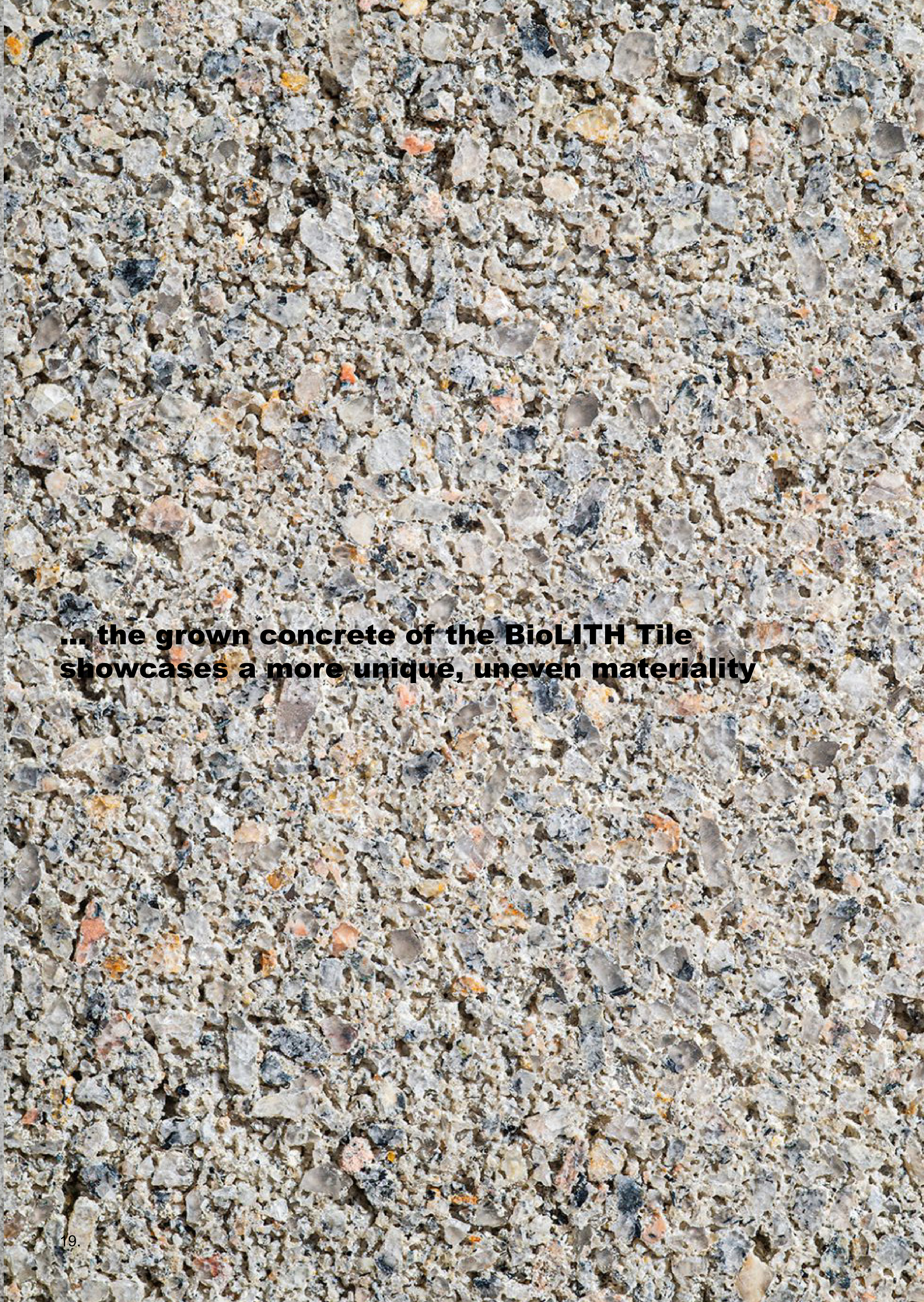
- Material scalability is limited by scalability of product types.
- More adaptable product types can help to compete with existing technologies and enable new typologies.
- Collective knowledge base models can help expand and explore product diversity, with both human and non-human collaborators.
- Nature can be a powerful co-designer explore product typologies beyond the ‘mimicry’ of conventional units.
- The nature of nature is local, not global: Human conceptions of scalability have inherent limitations within natural frameworks.
- Some degree of human control needs to be relinquished to locality, environmental unpredictability, and the agency of the microorganisms themselves.
- There are lessons to be learned through recognising ways that both living organisms, human and non-human, and architectural form can be influenced by and adapt to changing environments.
- Current regulations do not encompass the intricacies and complexities of biomaterials for construction.
- Like the world of microorganisms is so vast and varied, the material applications produced in collaboration with each microorganism can be similarly diverse.
- Adaptability in the ‘biologies’ of our frameworks may be needed to accommodate the inclusion of non-human life into building practice.
- Current methods of assessing sustainability are far from perfect and comprehensive, and themselves could benefit from looking to microorganisms and a more-than-human approach

- Geopolitical dynamics influence the availability of products and knowledge and can limit or enable the integration of novel materials.
- The global cross-pollination of ideas within the material communities, building upon a shared knowledge base, can accelerate research and development efforts as well as global availability and local production.
- Scepticism towards living in such close contact with microorganisms stems from a fear of the unknown ‘other’.
- The relationship between human and bacteria has been historically embedded in culture and architectural practice, and continues to shape architecture and design in new ways.
- We should continue to open ourselves up to explore the blurring of the strict boundaries between interior and exterior, good and bad and self and other through interactions with microorganisms, both in our bodies and buildings.
- The materials themselves embody the complex paradoxes of shifting paradigms towards microbial interactions, expressing control over environments yet embodying the agency of life to influence our actions and imagination.
- Limited access to costing in itself limits the use of the materials it is not accessible to compare them with conventional products.
- Natural growth cycles may be longer than mechanised production has become accustomed to, however they provide potential for additional phases and outputs through the organisms’ metabolic life-cycle.
- With this, we must be careful to be exploitive in our processes, ensuring that we are not exhausting the organism as resource and labour.

An understanding and application of this three-dimensional framework, as conducted in this thesis, has the potential to pave new pathways for practical, environmentally friendly and ethical futures for the production and integration of more sustainable building materials and new interspecies approaches into architectural practice.

The road does not end here. Let us continue to connect with and learn from our micro-neighbours, to explore ways to get to know each other and collaborate better, reduce our negative impact on the planet and embrace adaptability in our architectural practices.

While extracted concrete often expresses a monolithic aesthetic ...

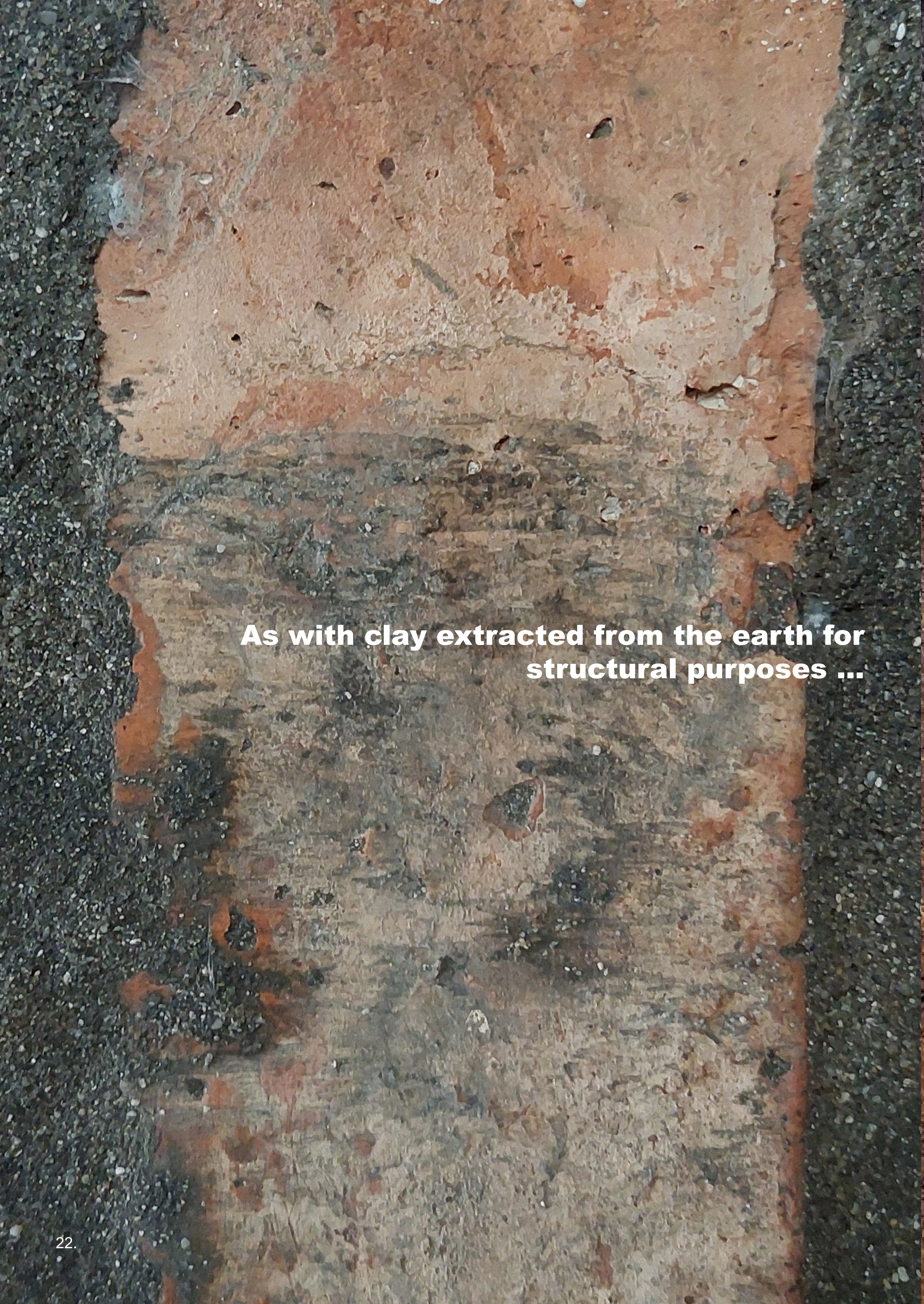


... the grown concrete of the BioLITH Tile showcases a more unique, uneven materiality

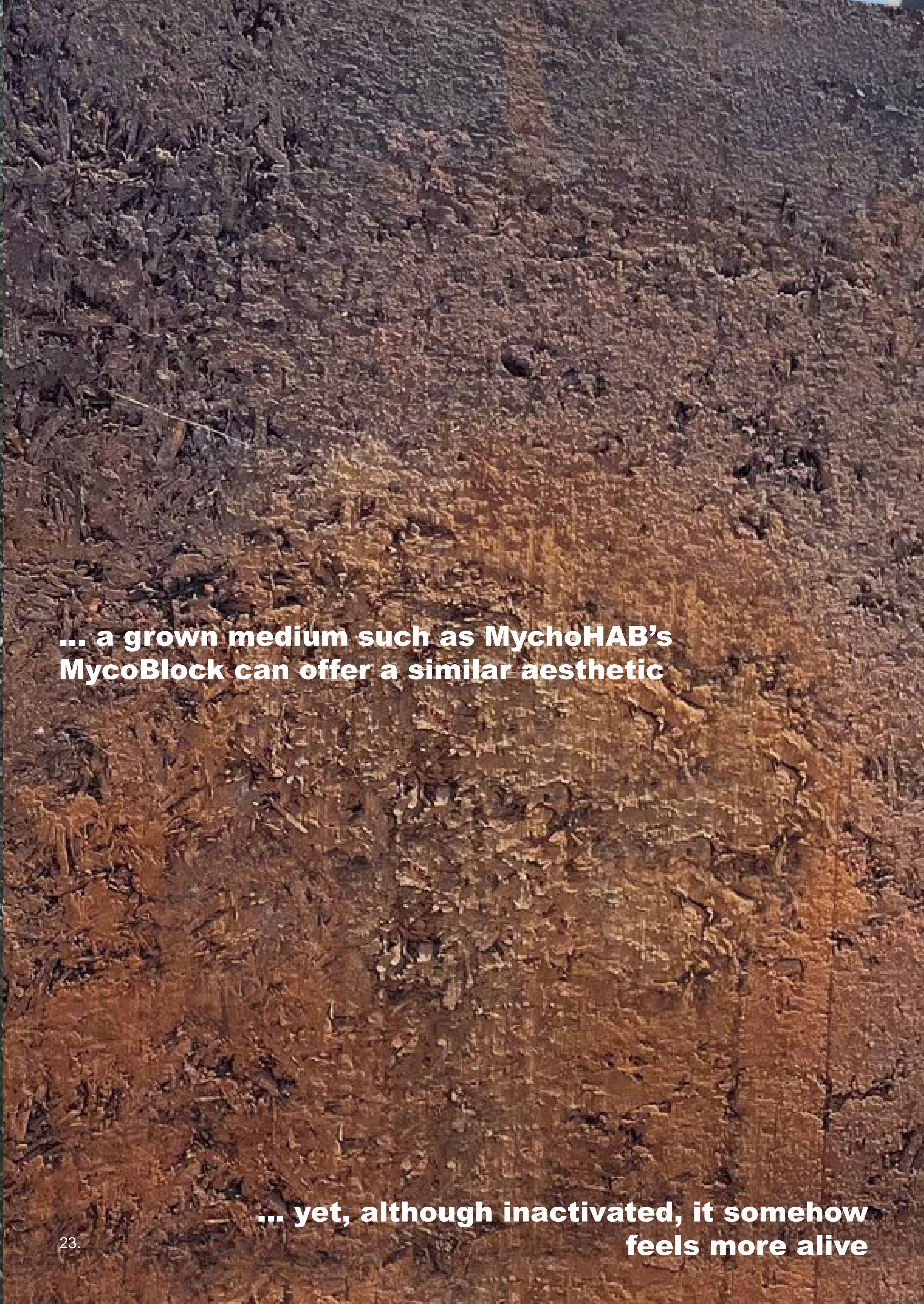
Yet the construction methods and forms of ordinary concrete masonry units ...

... are replicable with Prometheus Material’s masontry unit solution

... yet still the materiality and colour is reminiscent of a connection to nature

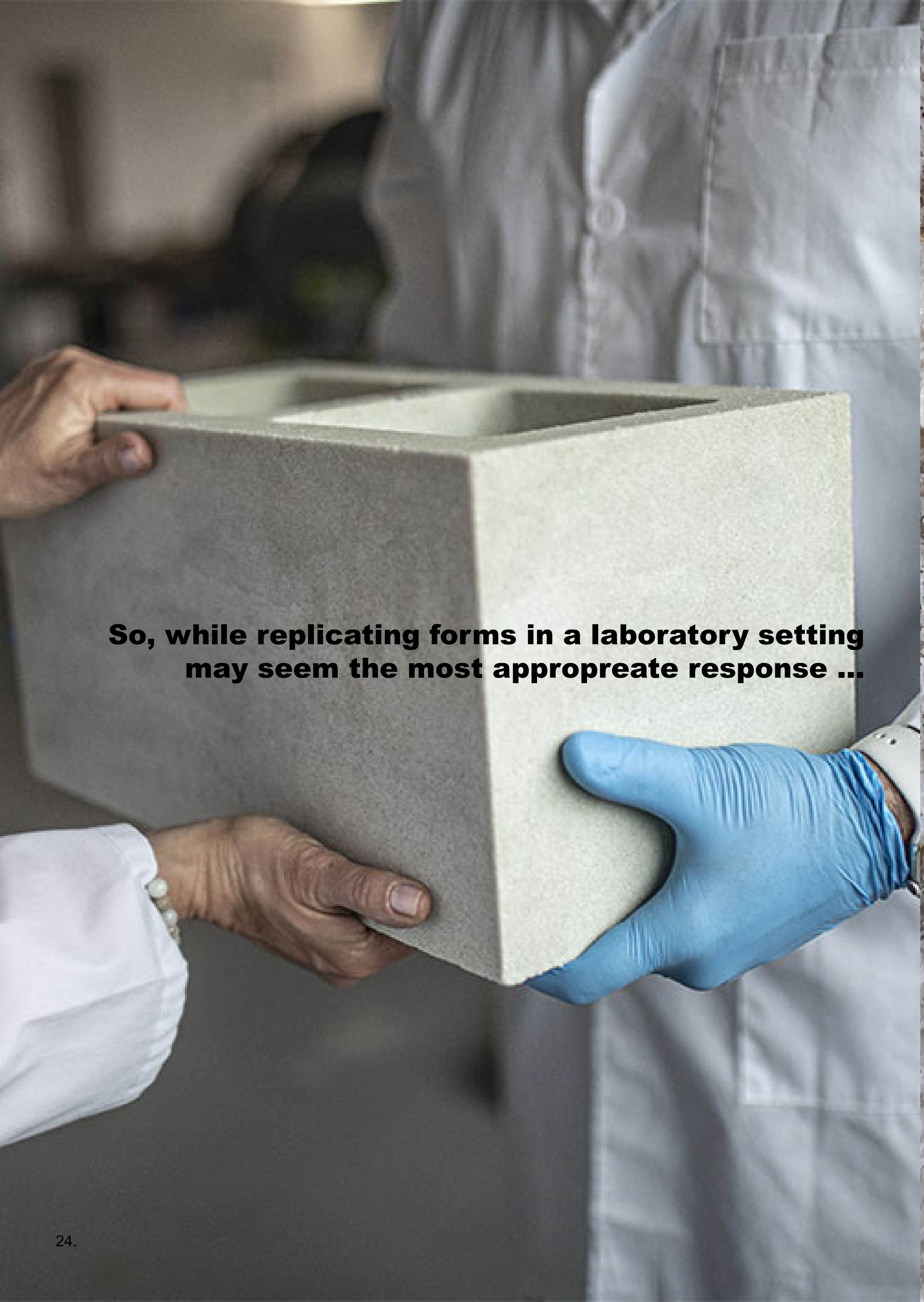


As with clay extracted from the earth for structural purposes ...



... a grown medium such as MychoHAB's MycoBlock can offer a similar aesthetic

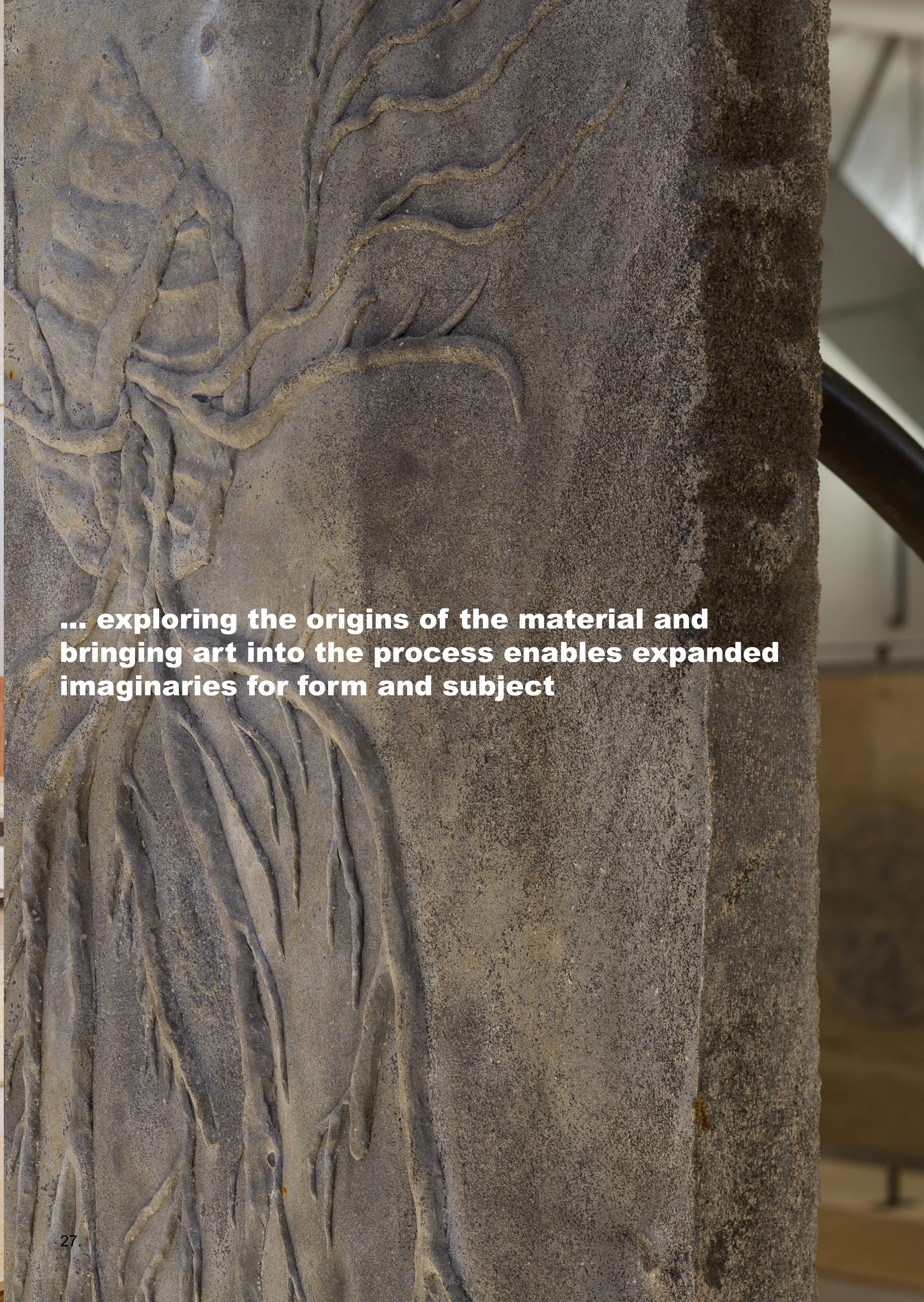
... yet, although inactivated, it somehow feels more alive



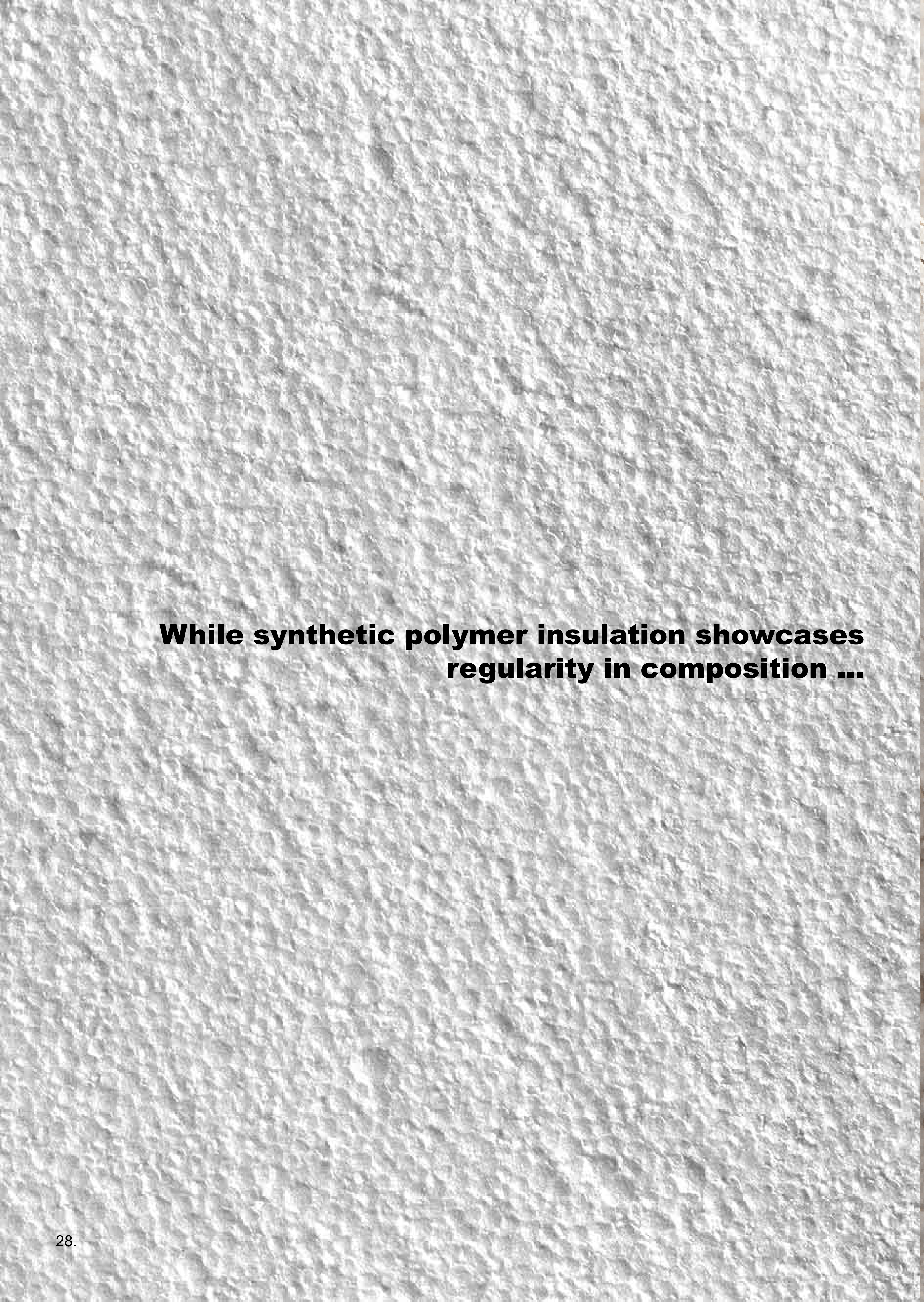
So, while replicating forms in a laboratory setting may seem the most appropreate response ...

... the organic roots of the technology are seeping into design imaginaries

So that even though the structural elements explored by GXN's collaboration with BioMason are expressed in rigid forms ...

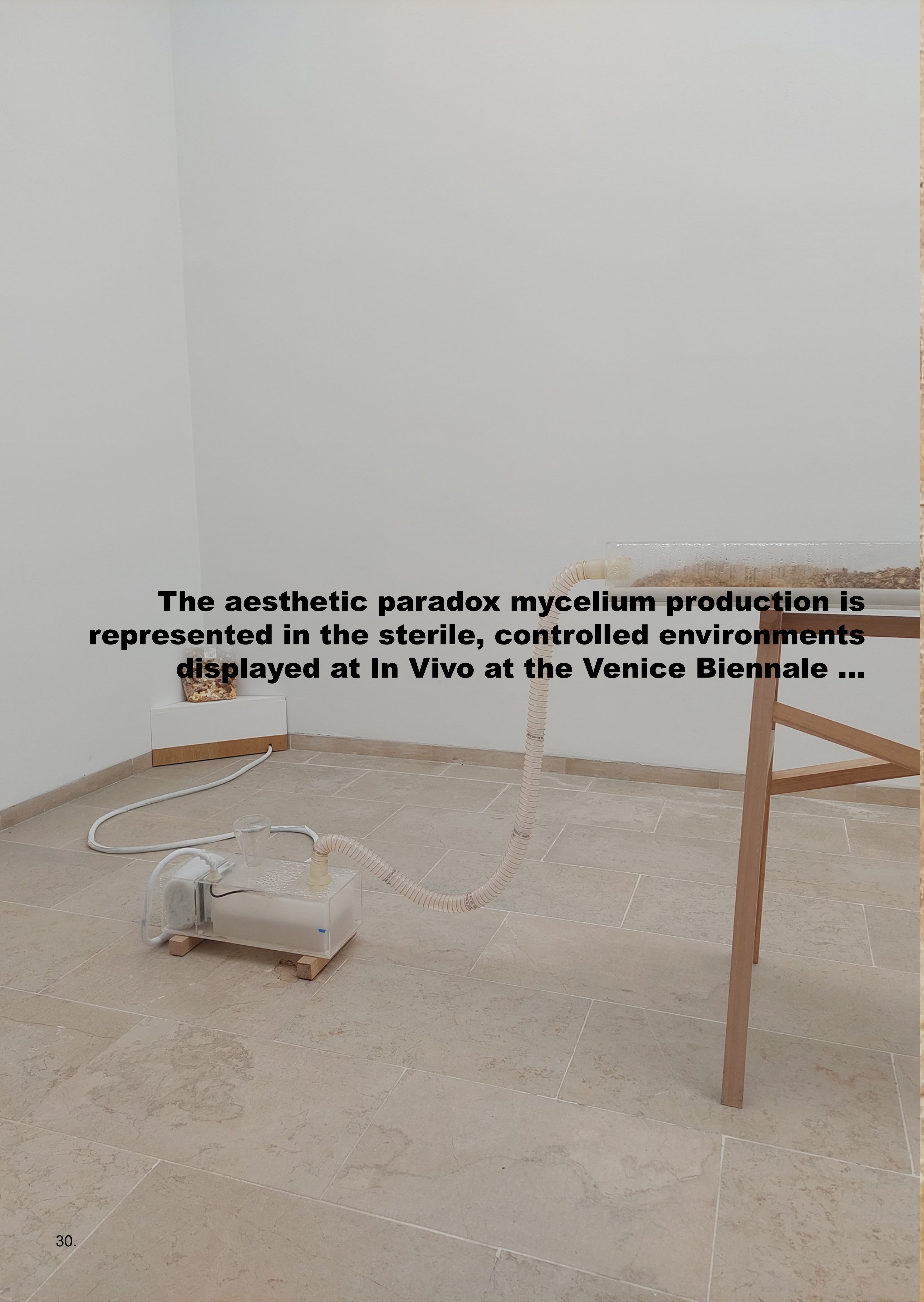


... exploring the origins of the material and bringing art into the process enables expanded imaginaries for form and subject

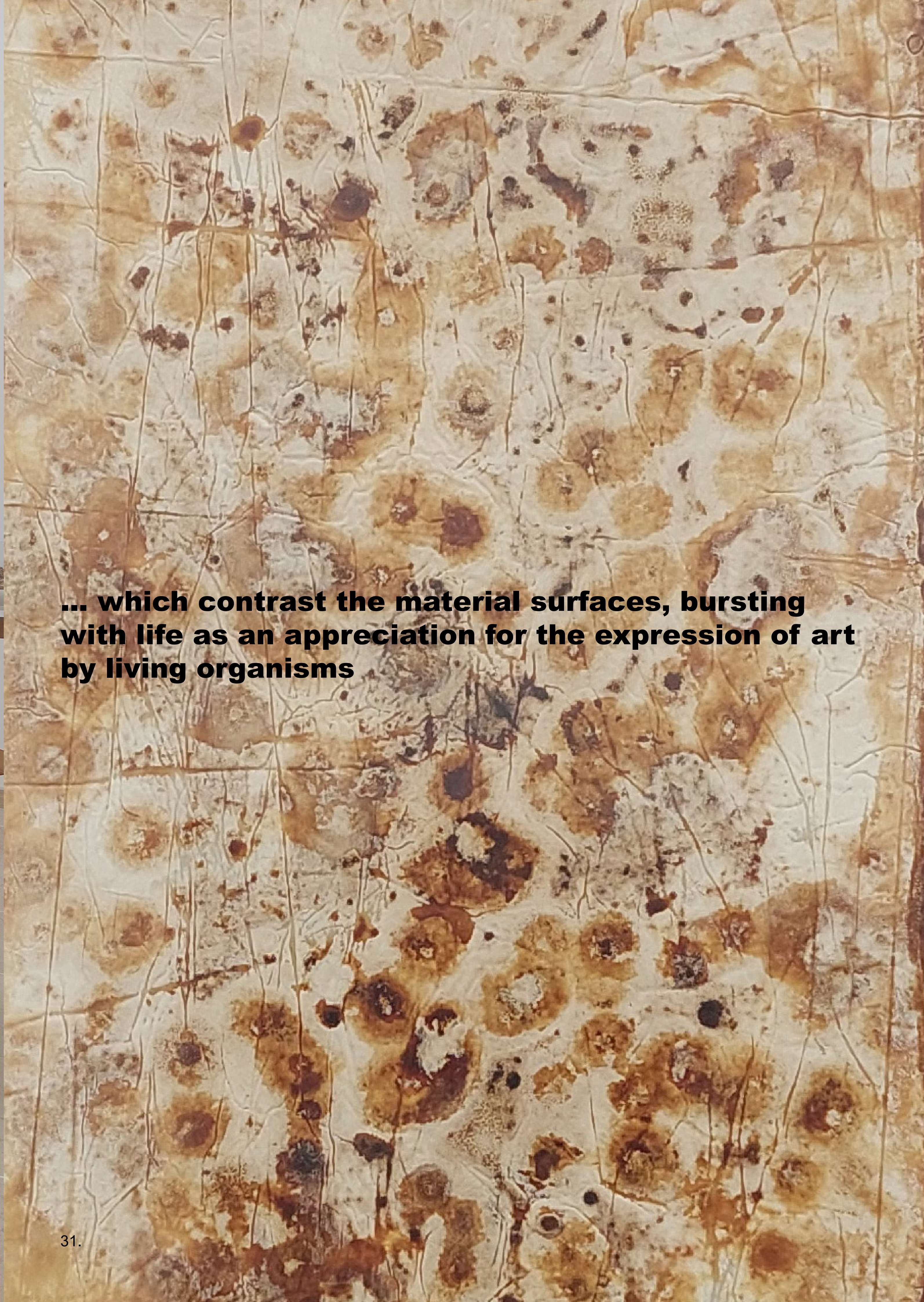


While synthetic polymer insulation showcases regularity in composition ...

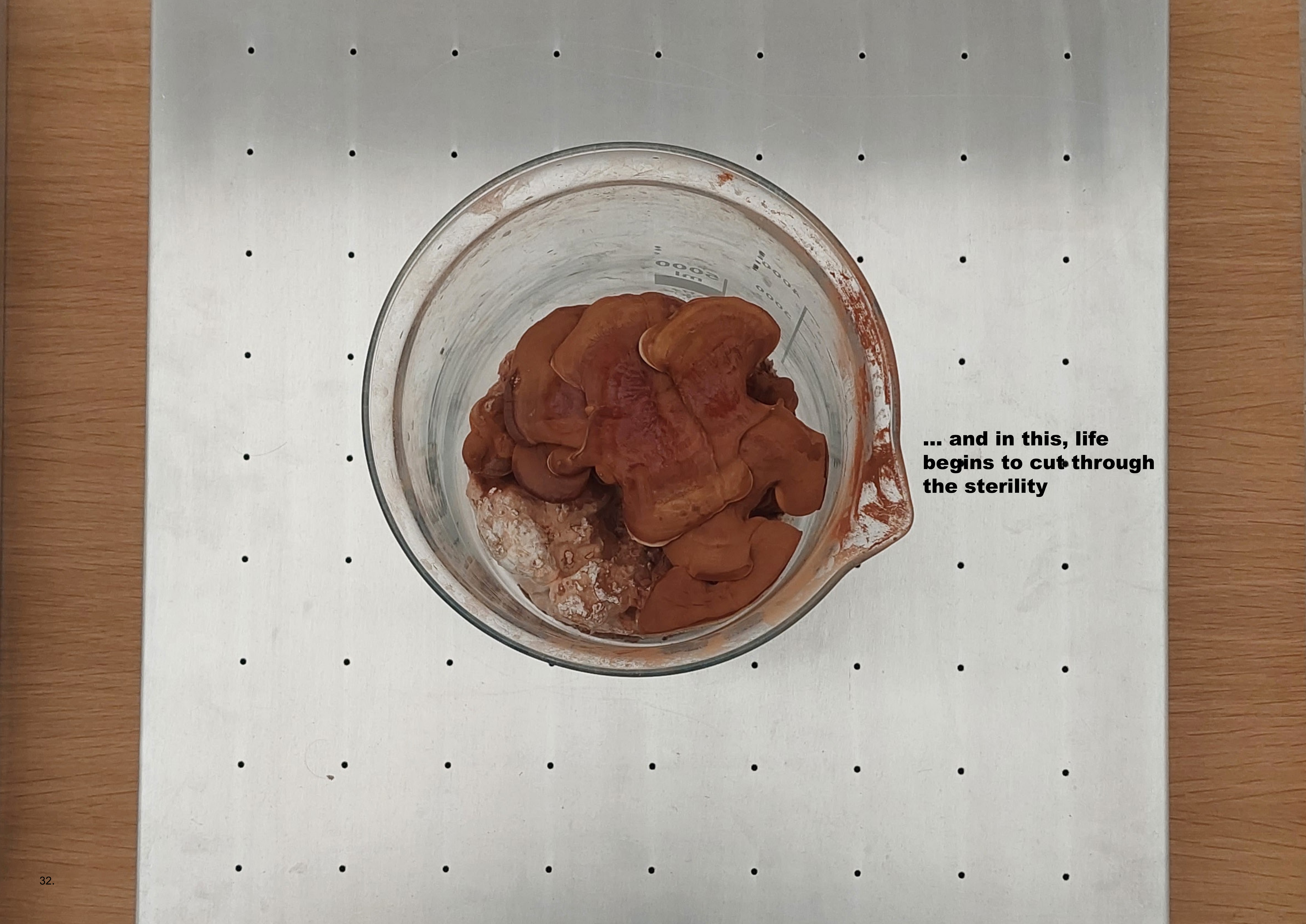
... the natural fibres of Ecovative Design’s MycoComposites express irregularity and variation



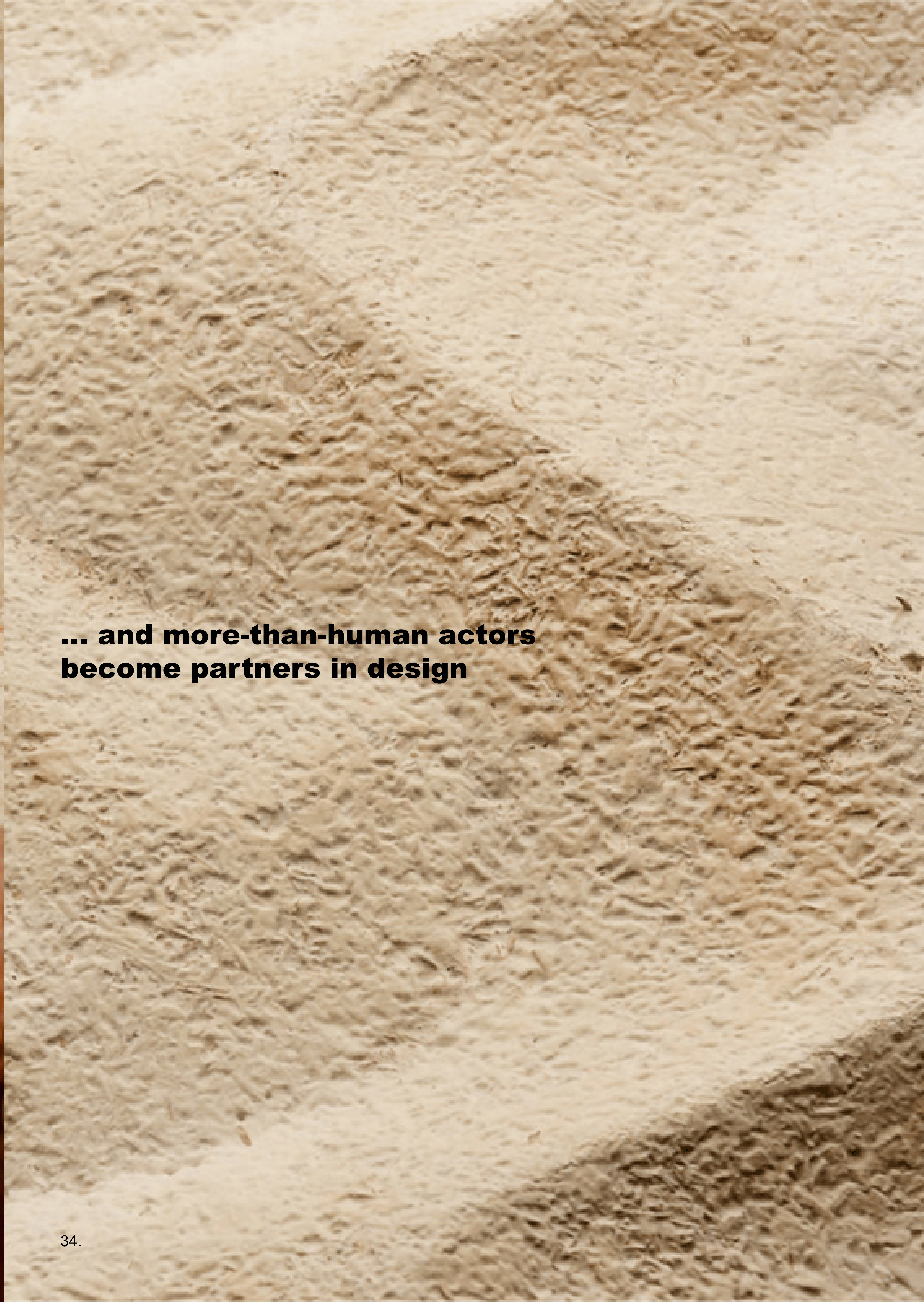
The aesthetic paradox mycelium production is represented in the sterile, controlled environments displayed at In Vivo at the Venice Biennale ...



... which contrast the material surfaces, bursting with life as an appreciation for the expression of art by living organisms



... and in this, life
begins to cut through
the sterility



… and more-than-human actors become partners in design

So, as the home turns into a laboratory ...

... life takes over the production process and our own creativity

... so that the future of architecture can be alive with new imaginations

Figure 18. *Concrete or cement texture or background:* conventional smooth concrete texture

Figure 19. *BioLITH tile natural:* BioLITH tile texture

Figure 20. *Masonry arrangement of ordinary CMUs*

Figure 21. *BioBlock Spiral wall masonry:* arrangement of Prometheus Material's masonry units as installed at Chicago Architecture Biennal

Figure 22. *Clay brick texture:* Photograph by author, 2024

Figure 23. *MycoHAB MycoBlock texture*

Figure 24. *Handing over Prometheus Materials masonry unit:* between lab workers in sterile conditions

Figure 25. *Biomineralisation in stony coral*

Figure 26. *Bioconcrete column in formwork*

Figure 27. *Bioconcrete artwork close up:* Silas Inoue's artistic expression of interspecies connections and solidarity using bioconcrete medium

Figure 28. *Polystyrene foam texture*

Figure 29. *MycoComposite component texture:* showing the soft, whitelayer of additional mycelial growth

Figure 30. *Humidity control:* supporting active substrate inoculation at Belgian Pavilion, In Vivo. Photograph by author, 2024

Figure 31. *Mycelium leather texture exhibited at In Vivo*: Photograph by author, 2024

Figure 32. *Mushroom growing in a beaker at In Vivo exhibition:* Photograph by author, 2024

Figure 33. *Second level mycelium growth creating surface layer:* on MycoComposite

Figure 34. *MycoComposite panel texture*

Figure 35. *Making MycoComposite:* preparing subtsrate to be innoculated by mycelium

Figure 36. *Mycelium growth*

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