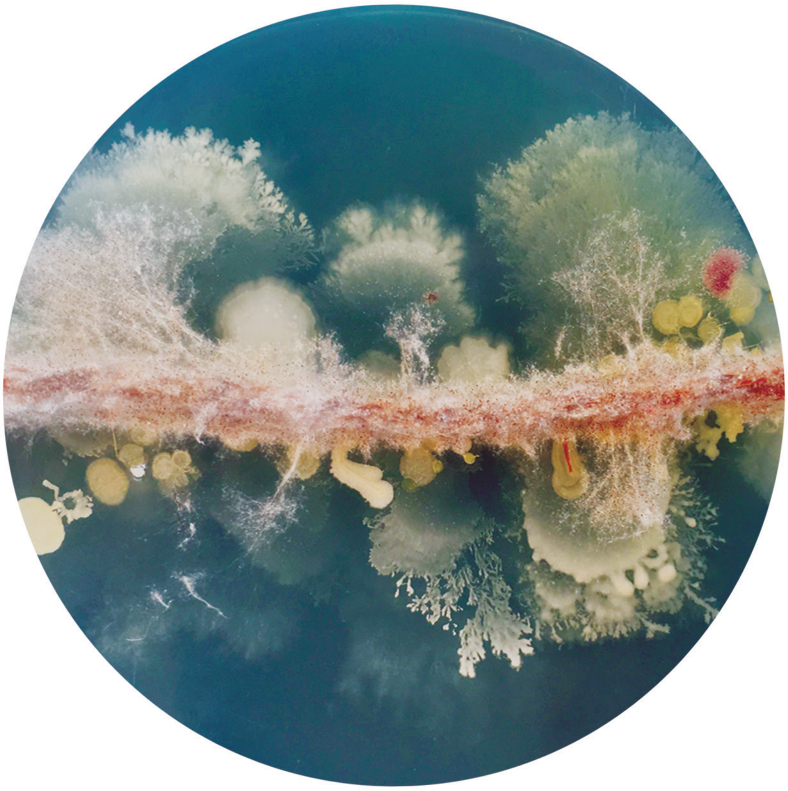

between duck and tree

metabolism-informed composite tectonics

PhD Thesis by

Bastian Beyer

Royal College of Art, London / 2019

Abstract

Architectural design and material innovation are reciprocally interconnected on multiple levels. The advancement of manufacturing techniques and processes, as well as new material qualities, open new performative and aesthetic prospects for architectural tectonics. Composite materials have constantly reshaped the field of construction throughout architectural history. The recent development of high-tech materials such as carbon- or glass-fibre has introduced entirely new structural possibilities, albeit their environmental impact is an issue of concern. The research therefore proposes alternative scenarios to utilise metabolism-informed manufacturing processes and bio-derived materials for a new generation of fibrous composites. This inquiry leads to a novel tectonic approach extending the expressive and performative repertoire of architectural design. Concomitantly, the idea of a responsive composite matrix investigates the emergent potential of material computation and biological systems for the architectural domain.

Embedding microorganisms into architectural material systems allows to harness their distinct characteristics and their structural metabolic by-produts, such as nano-cellulose or chitin fibre. Their propagation and metabolism is, to a large degree, influenced by the specific substrate and environment in which they develop. Textile systems present a suitable and, in the context of architecture, relevant substrate material. Due to their microstructure and material characterisitcs, natural fibres can facilitate the propagation of microbiological communities.

At the same time, fibrous systems offer wide range of fabrication techniques, such as winding, weaving or knitting, which can be harnessed for distinct textile tectonics. Textile materials allow the bridging of the scalar gap between the micro and the meso levels, and, combined with their wide-ranging geometrical potential, present a unique opportunity for spatial applications of biological systems.

The design and control of a distinct textile microbiome, with its distinct behaviour within a textiles system, enables the development of metabolic matrices and novel multi-hierarchical bio-composites. This underexplored class of materials can be utilised to generate material gradients and time-based, reactive or/and self-organizing behaviour dependent on the microbiome on a yarn level. Simultaneously they are offering a sustainable alternative to conventional composite materials. While the notion of performance in the context of building materials is generally reduced to solely structural characteristics, the concept aims to acknowledge the distinct performativity of natural systems embedded into material systems, which is explored in two distinct scenarios.

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For Marina

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Bastian Beyer

This thesis represents partial submission for the degree of Doctor of Philosophy at the Royal College of Art. I confirm that the work presented here is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

London, 03.04.2018

Bastian Beyer

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I'm reluctant about the idea of individual authorship – every thought process, work or idea is innately shaped and influenced by multiple actors through a process of exchange, friction and transformation between multiple domains. Most apparently (but not exclusively), this concerns the people directly involved in these processes.

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Thanks to my Uncle Michael, whose unconventional mechanical ingenuity still reverberates in my work.

Glossary of terms

The research borrows terminology from several fields beyond architecture. Therefore terms might differ semantically from their discipline of origin. The following section provides a brief introduction to some of the terms frequently used in the work.

Architectural composites:

In the context of the research, architectural materials or architectural composites are understood as intrinsically embedded in, and interrelated with, their environment. Unlike materials within the field of engineering, which mainly operate with a quantitative and target-oriented model, architectural materials also need to perform on a qualitative and interactive level. The material culture of modern composites, in particular, located between chemistry, structural engineering and technical fibre technology, lacks this qualitative and interactive dimension. The strong tendency towards fibre-based construction for architectural design, however, calls for an extension beyond mere technical performance and a re-evaluation of composites in relation to their qualitative features. Therefore a differentiation between composites and *architectural composites* seemed appropriate.

Ecology:

Ecology as part of the science of biology is concerned with the multiplicity of interdependent relationships between living systems and their environments. The research employs the term as an extended notion, including not merely living organisms but similarly dependencies and exchange processes between other actors such as environment, materials, microorganisms and systems. While “interdependency” would only describe a linear bi-directional relationship between two entities, the term “ecology” also connotes not only the relationship but simultaneously a boundary condition or field.

Fibre-based:

The research deals with naturally derived fibres which are extracted from cultured plant material. In a further step these fibres are spun into yarn, presenting a higher structural hierarchy. The explorations incorporate finished industrially fabricated yarn as a substrate to apply further geometrical, biological or chemical modification. However, as the design and treatment processes also consider the yarn level, the term “fibre-based” was chosen. In the context of the study it relates to all the fibrous constituents of a structural system

Demonstrator:

The notion of the term “demonstrator” in the context of the research generally aligns with the definition by Thomsen & Tamke (2009) (Figure 1), who understand it as “an application-led investigation allowing interfacing with real world problems and constraints”. Moultrie (2015) provides a finer distinction of various types of demonstrators. Although this concept is derived from the field of industrial design and is also concerned with product development and commercialisation, it also understands a demonstrator as a mediating “boundary-object” (p.11) and a tool for interdisciplinary communication.

Moultrie’s (2015) concept provides a detailed overview and categorisation for differentiating the various functions of a demonstrator. The demonstrators shown in this research encompass, but not limit themselves to, the distinct phases of development from supporting science and technology demonstrators to application demonstrators in a non-commercial context.

The first phases of the development are described as precursor science, and are manifested through supporting science and technology demonstrators in this research, substituted by the term étude.

Understanding and classifying the role of design demonstrators in scientific exploration (Moultrie,2015), infographic p.10

(Image redacted for copyright reasons)

Figure 1 demonstrator design approach (Moultrie 2015)

Étude:

The term is borrowed from the context of music, in which it is used to describe a musical piece intended for the practice of a specific technique or intonation for a specific instrument. Similar to a scientific experiment, an étude follows a predetermined set of instructions, in the form of musical notes, to reach a result through its execution. The role of the scientist in comparison with the musician, however, is inherently different. The scientist is an interchangeable, merely executive constituent during the carrying-out of the experiment. The musician, although similarly following very specific instructions in form of the notation of a piece, has a certain degree of freedom that allows an individual interpretation. The musician possesses integral, active and creative agency in the process of making. While the experiment is mostly result-driven, an étude is a vehicle to acquire new knowledge and skill-sets through the process of *making*.

Scenario :

In the context of the research a scenario is understood as a conceptual stage, a specific background which contextualises a demonstrator. The scenario functions as a narrative instrument, thus providing a platform for speculative elements and real-world settings to merge. The scenario enables the viewing of the project from multiple angles regarding its manufacture, application and relation to its environment. An indication will be made to the reader of whether the different elements of the scenario form a speculative domain.

Die Beziehungen zwischen Tragen und Lasten - dieses scheinbar für immer feststehende Gesetz - werden auch ihr Bild umdeuten müssen...

Erich Mendelsohn

1. Chapter 1: Structure and framework

1.1. Introduction

The unprecedented and recent challenges of petrochemical dependency, environmental issues and digitisation have fundamentally changed the architect's role. The contemporary condition calls for an extension of architecture's repertoire beyond formal and autotelic design towards an awareness for the intrinsic entanglement between material, environment and society. Concomitantly, this advocates for taking responsibility for the impact of design decisions and for responding to recent and global challenges. Building materials are in this context an important factor, and are directly related to architecture's environmental repercussions. Strategies such as geometrical and topological optimisation, in combination with material engineering and contemporary manufacturing methods, offer the potential to contribute to a more efficient and sustainable use of building materials. Simultaneously, embracing novel material processes and production strategies inherently entails an impetus for new aesthetics to unfold.

Composite materials, whether natural or man-made, are among the oldest materials used for construction. Their engineering dates back as far as the first straw-reinforced bricks used by ancient Egyptian cultures (Campbell, 2003). Similarly, the use of wood, a biologically derived natural composite, is deeply rooted in human culture, as well as architectural heritage (Noble 2017). Composite materials have recently undergone a renaissance within the field of architecture due to their combination of lightweight, structural performance and customisability (Fleischmann et al. 2012). Their performance, however, is generally reduced to their structural behaviour alone. In the context of architecture their performative profile is due to undergo a reconsideration in relation to their potential beyond mere quantitative characteristics.

The generation of composites in nature displays many examples of intelligent structural formation processes in relation to their environment (Zolotovsky 2017). Biological systems offer unique characteristics for reactive and adaptive building materials (Cruz & Beckett 2016). Recent developments within biotechnology, induced a shift within contemporary biology, transforming the discipline from a mere observatory to a generative practice (Luisi 2007; Ellis et al. 2011). This shift of paradigm offers the potential not merely to extract resources from nature but also to generate new materials through nature. The notion of metabolism provides a systemic blueprint for dynamic systems and their generative relationship with their environment.

The application of biological systems within architecture and design demands an extensive consideration of substrate materials and scaffolds to bridge the scalar gap between nano and macro scales. Fibrous materials thereby offer a suitable medium for a designed textile microbiome, allowing for a controlled spatial application of biological systems. The interdependency between fibrous substrate and microbiological agent results in a sui generis class of composite materials which utilises nature's inherent autopoiesis within a material system comprised of a bio-active matrix and a fibrous substrate. Textile manufacturing methods thus provide a superordinate geometry for the fibrous system. The interplay between the three main focal areas – matrix, fibres and geometry – contribute equally to the outcome, thus framing the research strategy.

The concept demands a holistic and interdisciplinary research approach encompassing the fields of design, biology and textile material engineering and manufacturing. The aim is to explore the notion of biological metabolism as a design driver for architectural construction and to deepen the understanding of the complex relationship between microorganisms and textiles to map out future potentials for novel design applications. The research centres around the question of how biological agency can be implemented into fibrous tectonics and their generation.

1.2. Thesis Structure

The thesis[1] comprises seven chapters investigating composite materials - their manufacture and tectonics - informed by processes of biological metabolism.

Chapter 1 will outline the methodological framework within which the project operates and provide a statement in regards to sustainability objectives.

Chapter 2 sets the historical and design-theoretical context in which the research is located. The project proposes a synthesis of knowledge and methods from the fields of architecture, material engineering and textile design to unfold new potential for the domain of fibre-based composite materials. Firstly, a short introduction to the field of textile tectonics is provided, which includes a comprehensive overview of the underlying textile form-giving strategies. Subsequently, a discourse into the notion of tectonics within architecture and its boundary conditions aims to speculate on alternative tectonic expressions. This is followed by an overview of composite tectonics in a historical and contemporary context, encompassing their manufacture and expressive potential, framing the context of the research. Furthermore, a critical inquiry into the notion of the performativity of architectural materials, with specific attention to fibre-based composites, leads to the concept of the autopoiesis of biological systems and sets the stage for the following practice-based scenarios.

Chapter 3 discusses aspects of performativity in biology, and introduces the notion of biological metabolism.

Chapter 4 introduces a mechanistic metabolic analogy with reference to the automatons of the European Enlightenment, the Metabolist movement within architecture and the notion of autopoiesis. Jaques de Vaucanson's *Canard Digérateur* ("the digesting duck") sets the background for Scenario 1 and Demonstrator 1 (Turm 2) (Figure 2). The presented project is concerned with an autonomous allopoietic winding system for fibre-based composites and its reciprocal relationship to its environment. It focuses on the context and time-based transitional states of material and systems.

Chapter 5 moves away from the biological analogy to investigate the direct application and integration of microbiology within material systems. An overview of the field is provided, with specific focus on the importance and interdependency of substrate and biome. After this, the

1 The research was undertaken in as part of a EU research program, called ArcInTex, which was set up to explore the exchange between architecture, interaction design and textiles (see appendix A).

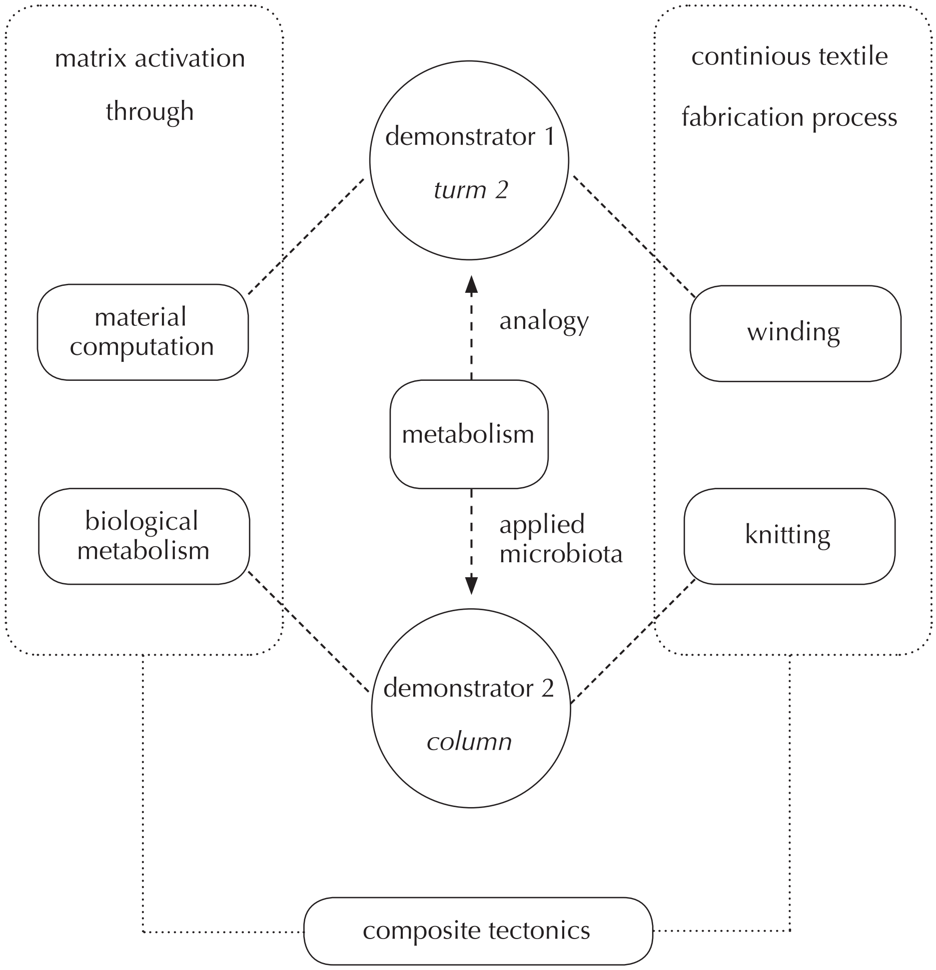

Figure 2 Demonstrator objectives

concept of an active textile microbiome for fibre-based materials and metabolising matrices is introduced and illustrated by a series of biomic explorations.

Chapter 6 introduces the main focus of the research: the implication and design of an active textile microbiome for metabolising matrices. In this context, analogies to a tree as a living fibrous composite is drawn and explored through three études.

The études are presented to test the concept of an active textile microbiome in relation to its application and activation. An introductory chapter for each étude provides a contextualisation and outlines the aims of the specific setup. The three individual projects facilitate acquaintance with their specific biotechnical protocols, as well as the properties and behaviour of the selected microorganisms. Each étude deploys a distinct active microbiological agent as an actor on a fibrous material system. Furthermore, the demonstrator "column" as part of Scenario 2 is introduced (Figure 2). The chapter discusses the development of the substrate as well as the setup and treatment of the material in detail, and concludes with an assessment of the challenges of scale in relation to the microbiological process, textile material and behaviour of a textile composite system.

Chapter 7 critically assesses the overall project and its contribution to knowledge while providing a future trajectory for the project. A comprehensive reflection outlines the personal engagement in, and perspective on, the project.

1.3. Methodology

> A designer has the right and the duty to employ information from any and every field of knowledge that happens to be relevant to the case in hand. In this sense, the body of knowledge in support of Design has to be regarded formally as unbounded. (Archer 1991, p.20)

Architecture in general is an inherently interdisciplinary and dialectic practice which involves a wide range of fields and actors in its making. It operates and mediates between the humanities and technology, and therefore advances in these fields reciprocally inform architectural practice (Palz 2012). Whereas architectural research usually arises from an architectural perspective or question, the following research aims to concurrently find questions and possibilities relevant to the field of architecture *through* the studies of other fields.

The practice-based research explores new perspectives on the performativity of fibre-based materials and their generation. This entails the navigation of a multi-disciplinary spectrum, encompassing material engineering, computational design, (process) design, textiles and biotechnology. The research thus operates within an inter- and transdisciplinary[2] framework (Nicolescu 2002; Mittelstraß 2011; Bernstein 2015). The enquiry borrows methods, concepts and processes from various disciplines, and embraces the generalist nature of architecture. The flexibility to exchange the disciplinary lenses and focal points allowed the researcher to locate and be inspired by systemic overlaps and coherences of different fields. However, the decision to liaise with a broad disciplinary spectrum holds the danger of losing the depth of engagement. In order to avoid this risk, collaborations, consultations and discussions with specialists were initiated at all critical stages of the projects.

Design research, according to Christopher Frayling (1993), can be classified by a differentiation between research into, through or for design. Throughout the project the angle and focal points vary; however, the full spectrum of design research is utilised.

Research into design (historical and contemporary) aims to contextualise the importance of architectural material in general for architectural and human culture. Research through design allows the investigation of new processes and materials through the act of making, whereas ultimately research for design produces outcomes where thinking is embodied in the artefact, as well as providing a framework for future design investigations (Frayling 1993).

2 A discursive investigation into the notion of inter and transdisciplinarity and the relevance for this research is provided in appendix B

The project navigates between design research and scientific enquiry. Both approaches share the initial pursuit of an appropriate solution to a problem and/or question. However, while a scientific experiment tries to reduce the complexity by eliminating variables and parameters to find one exact answer, design investigations distinguish themselves by embracing the complexity of multiple variables, and might even provide another question as a valuable solution. In this tradition the project embraces a meandering, mixed methodology in which the methods described in the following paragraph are understood as conceptual and technical focal points, whereas the actual process of thinking and making is negotiated in the interjacent bokeh.

Action research (Archer 1995), which involves the investigation and physical making of process design probes, études and demonstrators, allows the testing of some of the concepts outlined in the research. Archer (1995) argues that

> There are circumstances where the best or only way to shed light on a proposition, a principle, a material, a process or a function is to attempt to construct something, or to enact something, calculated to explore, embody or test it. (p.11)

The research utilises demonstrators, etudes and scenarios to test and speculate on novel modes of fabrication and their potential for textile tectonics. New architectural design vocabulary thus emerges through the combination of in-situ manufacturing and the time-based, processual characteristics of bio-fabrication. The research investigates the interface of biotechnology, textiles and architecture in order to find new expressions for the processual manufacture of bio-active textile composites. The processes and means of fabrication in the domain of biotechnology differ from the ones applied in architecture. By locating the differences and overlaps on an infrastructural, aesthetic and conceptual level, novel hybrid approaches towards material generation emerge.

The generation of qualitative and quantitative data allows for an evaluation of the concepts explored. Quantitative data provides a foundation for structural simulation and classification. However, as architectural materials are inherently embedded in a dynamic socio-cultural and environmental context, a merely quantitative view on architectural materials would not adequately present the complex nature of potential architectural materials. Therefore a qualitative and subjective perspective needs to be established to account for their complex nature.

The presented research sets out to reframe the performativity of fibre-based composites through the methodology previously outlined. Throughout the project, biological metabolism serves as a conceptual leitmotif and will be approximated by two demonstrators through different means of conceptualisation, representation, material and design.

1.4. Sustainability statement

Material innovation, from a personal viewpoint, should be self-evidently rooted in a discourse of sustainability. Throughout the enquiry, different material studies are presented which approach sustainability from different angles. The majority of fibre-based composite materials is dependent on petrochemical resources, and their manufacture is highly energy-intensive (US Department of Energy 2015). The majority of approaches to recycling composite waste material are in reality a downcycling process where the recovered materials do not merely regain their initial performative properties (Witik et al. 2013; Oliveux et al. 2015).[3]

The highly pollutive building and construction sector is one of the most significant producer of greenhouse gases (UNEP 2016). Therefore, architects have to take responsibility in counteracting this development. Amongst other strategies, such as the reduction in operative energy consumption and the use of sustainable energy and materials, the design of innovative material systems and construction techniques can contribute significantly to a reduction in the environmental impact of architecture (Cruz & Beckett 2016; Benjamin 2017).

This correlation between sustainability and architectural design operates as a fundamental paradigm for all the material experiments presented; In-situ manufacturing enables the saving of energy for transport while bio-based and bio-derived materials present a renewable alternative to conventional building materials. Although a quantitative analysis in relation to the environmental impact and use of energy was beyond the scope of this investigation, the use of biologically derived, renewable and degradable materials as well as biological processes provides a profound basis for sustainable material development.

3 Appendix D discusses this issue in detail while providing an overview of the field of green composites

2. Chapter 2: Context

2.1. Textile tectonics

The use of textiles in an architectural context is rooted in an extensive technological and cultural history (Garcia 2006). Their membranous and lightweight character presents a soft and dynamic antidote to rigid load-bearing structures. Ancient vernacular textile architecture such as yurts and tents provided an alternative to heavy wood or stone construction – a lightweight, transportable shelter which could be set up in a relatively short time using only minimal tools. These textile-based typologies and construction principles catered for the mobility and infrastructure of nomadic cultures to present an early example of a tectonic approach to textiles.

The manufacture of fabric and its underlying logic of interlacing, interweaving or winding offers a unique assembly principle with distinctive material continuity and geometrical and performative variance (Palz 2012). Textile principles challenge conventional techniques of structural joining through their unique material continuity, resulting in structural interdependency between local and global conditions. In his pivotal book "Der Stil in den technischen und tektonischen Künsten", Semper (1878) provides an extensive taxonomy of early techniques of textile joining and construction principles, constructing his "Bekleidungtheorie", the "theory of dressing", which alludes to the structural dependency between textile and load-bearing systems. Semper here makes a case for link between textile culture and the advance architectural form (Spuybroek 2011). Beyond this structural and technical dependency, Semper conceives the textile logic and its space-giving and expressive potential as being in deep connection with human culture and craft, elevating the mere tectonic view to a means of communication and interaction (Palz 2012).

The geometric logic of textile manufacture follows a unique simplicity and structural beauty. A yarn, emancipated from its physical materiality, renders a line in space with a defined beginning and end. Through a choreography of geometrical manipulations, such as interweaving or interlocking, a mesh emerges. This mesh embodies the distinct geometric operations and constitutes a transformation from a line to a plane (mesh). This fragile construct is dependent on physical materiality and the resulting friction, collision, tension and weight (Lomov et al. 2001) to maintain its structural integrity.

Modern tectonic applications of textiles range from robotically manufactured structural composites (Doerstelmann et al. 2015) to high-tech membranes (Thomsen et al. 2015). Although they expand the expressive and functional repertoire of textile tectonics, they are fundamentally and inseparably connected and dependent on textile logics which refer back to our ancestral knowledge and culture of textile materials.

2.2. Structural logic

The research navigates the potential of fibre and textile-based material systems in the context of architecture. The following section introduces three fundamental technological and structural principles inherent to textile materials. The research utilises, designs and interacts with these characteristics on several levels: their conceptual interdependency is thus vital for the project's trajectory.

A. Hierarchy

Textiles are inherently hierarchical structural systems (Lomov et al. 2001; Palz 2012). They can be classified into three main scalar hierarchies, starting from the fibre level, moving through the yarn level and up to the level of fabric (Lomov et al. 2001). The structural properties and behaviour of textiles emerge from the complex interplay between these three main factors. Reciprocally, this relationship can be harnessed to influence and design specific characteristics.

These hierarchies are accompanied by a set of sub-hierarchies, which similarly influence the whole system. Natural fibres, for instance, are composed of a fibrous sub-system defining their structural behaviour (Zolotovsky 2017). Similarly, higher-order hierarchies in the form of layered textile or reinforcements extend the spectrum of behaviour. Their distinct hierarchical constitution opens an extensive range for design to engage on every level. The field of technical textiles, as well as that of the functional clothing industry, makes use of this opportunity to engineer the desired characteristics (Horrocks & Anand 2010). This field relies on an established design pipeline, which ranges from the yarn up to the textile level.

Historically, these emergent properties were subject to empirical testing and detailed experiential knowledge of fibre properties, manufacturing methods and textile structures. Contemporary computational approaches offer simulations to predict their behaviour, albeit employing means of simplification and rationalisation to reduce their complexity (de Araujo et al. 2004). For a holistic modelling approach, multiple factors, such as intra-yarn properties, yarn-yarn collisions or dampening and friction parameters, would have to be accounted for (Kaldor 2008). Engaging in the hierarchical interdependencies of textile materials through design unfolds new potential and enables manipulable properties to be embedded at the fibre and textile level (Palz 2012). This distinct hierarchical character and their dependencies will be explored in further detail during the research.

B. Continuity and topological consistency

The majority of textile manufacturing methods rely on continuous raw materials such as yarns or monofilaments. Textile structures emerge through further manipulation, either by textile craft or with specific machinery. In this way the yarn's geometry changes fundamentally, from a straight line to a distinct set of curvatures and radii dependend on the equilibrium between the multiply occurring forces during and after manufacturing (Kaldor 2008). The yarn's topology, however, remains constant.[4] This is inherently in contrast to the manufacture of other materials and their reconfiguration during processing. The processing of wood or cement into any shape demands a process which changes both their geometry and their topology.

C. Anisotropy

Depending on their geometry and origin, fibres and yarns display directional and heterogenous properties. While synthetic fibres possess a homogeneous materiality, their geometry accounts for their directionality (Elsasser 2010). Besides their geometry, natural fibres are themselves constituted from a sub-set of materials which additionally present a distinct directionality (Zolotovsky 2017).

On a higher hierarchical layer, fibres form a fabric which similarly displays directional behaviour depending on their distinct geometry resulting from the applied textile technique (Taylor 1990). While incorporating the same yarn, only the selection of textile manufacturing techniques, such as knitting or weaving, would result in a definitive change of structural behaviour. Knitted textiles generally offer high elasticity in vertical and horizontal directions, while weft structures offer increased directional stability but lack, without diagonal insertions, a resistance to sheer conditions (Elsasser 2010).

An exception are non-woven fabrics, which display a high directional stability and offer through their structure a very similar behaviour to their fibre constituents (Elsasser 2010).

While the introduction of material gradients and manipulable properties to solid materials such as plastics or metals calls for a reconsideration of manufacturing strategy: textiles can be adapted to specific engineering demands solely through the geometric manipulation of their yarn structure, while maintaining a constant yarn materiality (Palz 2012). This can be achieved through various fabrication techniques and/or patterning (Udupa et al. 2014).

4 For this argument the yarn is simplified as a solid pipe which is deformed through textile processing. While through this operation the geometry (relative position in space, curvature) changes, the topology (basic shape properties of a pipe) remains constant.

2.3. Form-giving principles

Most fabrics are inherently soft and and malleable. The interaction with textiles innately results in complex and ephemeral expressions, however, in order to render a permanent shape, textile structures depend on primary structural conditioning principles. Herewith, a reciprocal structural and topological dependency emerges between the textile and the form-giving entity. This relationship results in a distinct shape manifesting the equilibrium of the forces that occur between the structural entity and fabric. In most cases the fabric retains its membranous character while being activated through distinct edge-conditions or point-loads. The following section discusses four main form-giving principles for fabric-based structures.

A.Draping

The most basic form of achieving a permanent spatial configuration of a fabric is achieved through the process of draping. In this way fabric is used to cover a structural element or geometry. The fabric is held by in position by its own weight and the geometry of the substructure.

The resulting shape of the fabric is determined by multiple factors, such as self-weight, fibre materiality and the textile manufacturing method (knitting, weaving, etc.). The fabric mediates the different parameters and settles in a state of equilibrium. (Figure 3 , Figure 4)

B.Hanging

Hanging is one of the most common practices of applying textiles in the architectural context. Curtains or shading elements utilise this principle to generate light and dynamic spatial separators or visual barriers. This technique fixes one or more edges or points of the fabric to a static structure. Whereas in the case of draping the structural element is located underneath the fabric, a hanging configuration usually utilises a structure beside it (a flag) or above it (a curtain). The form-giving factors are similar to the draping process – self-weight, textile structure and material. Furthermore, aerodynamic conditions can influence the textile configuration and animate the expression. (Figure 5, Figure 6)

C. Tensing

A tensile textile system requires two or more fixed edges of a textile to apply force in opposing directions. This setup tenses the textile and results in a shape which renders a minimal surface, which is similarly influenced by the self-weight and individual fabric characteristics, between the two fixed edges. Knitted fabrics, in particular, with their distinct elastic properties, are suitable for tensile systems. Due to their high customisability and CNC (computer numerical controlled) manufacturing, their properties can be engineered and tailored for specific applications. Simultaneously, features such as reinforcements, channels or pockets can be already incorporated at the manufacturing stage (Thomsen et al. 2015).(Figure 7, Figure 8)

D. Embedding

This strategy presents a special type of conditioning, and is differentiated from the other approaches by a structural matrix embedded within the textile (Figure 10). In the previous examples, the form-giving structural element is clearly distinct in regard to its materiality and relationship to the fabric. The fabric retains its membranous character while the substructure is similarly unaltered in its behaviour. A embedded structural matrix permeates the fibrous structure and forms an inseparable and structural composite material which, in its appearance, is monolithic (Hull & Clyne 1996) (Figure 9). Although the matrix and reinforcement function as one material, the individual constituents account for distinct load cases. While the matrix material provides structural stiffness and performs in compressive load cases, the embedded fibrous/fabric element is utilised as a reinforcing element, compensating for tensile loads (Gay & Hoa 2007). Embedded matrices enable distinct structural behaviour; however, unlike the case of the other strategies outlined above, this does not imply a distinct form-giving principle. In regard to their shaping, temporary draping, moulding or tensing methods, as discussed above, have to be applied. However, once the composite settles into shape and is cured these measures can be removed and the material retains its shape.

The specific focus in this research is on the materiality and on embedded matrices, and how they contribute to the generation of composite tectonics. This specific transitionary state from soft to rigid is, in the context of the research, of particular interest. The following chapter discusses the use of fibre-based composite materials in the architectural context.

Figure 3 historic yurt, vernacular textile tectonics

Figure 4 Yurt structural substructure

Figure 5 Velvet and Silk Café, Mies van der Rohe, Lilly Reich (1927)

Figure 6 Velvet and Silk Café, Mies van der Rohe, Lilly Reich, floorplan (1927)

Figure 7 Hybrid Tower, KADK (2016), knitted tensile construction

Figure 8 Hybrid Tower, KADK (2016), knitted tensile construction, construction detail

Figure 9 Carbon fibre composite component

Figure 10 Embedded structural resin matrix

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Yurt image: http://www.karakalpak.com/yurthistory.html

(Image redacted for copyright reasons)

Yurt substructure image: http://www.karakalpak.com/yurthistory.html

(Image redacted for copyright reasons)

Velvet and Silk Cafe:

http://socks-studio.com/2016/02/29/cafe-samt-seide-by-ludwig-mies-van-der-rohe-and-lilly-reich-1927/

(Image redacted for copyright reasons)

Velvet and Silk Cafe Floorplan:

http://socks-studio.com/2016/02/29/cafe-samt-seide-by-ludwig-mies-van-der-rohe-and-lilly-reich-1927/

(Image redacted for copyright reasons)

Hybrid Tower KADK:

https://kadk.dk/en/case/michel-schmeck-simulating-textile-hybrid-structures?gallery=15170

(Image redacted for copyright reasons)

Hybrid Tower KADK detial:

https://kadk.dk/en/case/hybrid-tower

(Image redacted for copyright reasons)

Carbon structure:

https://www.graco.com/gb/en/products/materials/composites.html

(Image redacted for copyright reasons)

Carbon structure microscopy:

http://2.bp.blogspot.com/-hGnzNJ9Mim0/UXMme2jEcrI/AAAAAAAAAJg/tfJJnrFkrFs/s1600/image-05-large.jpg

(Image redacted for copyright reasons)

2.4. The tectonics of fibre-based composites

The field of fibre-based composite materials encompasses an extensive range of materials, fabrication strategies and applications. The focus for this study is the distinct tectonics enabled by textile-based composites and their manufacture.

The following chapters incorporate a comprehensive overview of composites and their relevance for the field of architecture, from a historic, contemporary and manufacturing perspective. A selection of fabrication methods is presented to frame the morphological and structural potential of composites. In conclusion, the notion of performance is discussed in the context of composites.

A. Historic

Composite materials present a uniquely versatile and complex class of materials. Whether of natural or man-made origin, they have been integral to human construction, and are therefore inseparable from our architectural building culture and heritage. This knowledge, enduring and developing over centuries, is constantly expanding and evolving. New tools and materials enable the fostering and extending of new possibilities of composites for construction.

Generally, composites can be described as a combination of two or more chemically and physically differing sub-materials, forming one monolithic material (Gay & Hoa 2007). The individual materials remain distinct within the finished material, so a synergetic effect is thus obtained in which the combined materials foster properties which cannot be achieved by either of the components alone (Åström 1997).

The materials are usually composed of one continuous phase, the matrix, and one discontinuous phase, the reinforcement, which can consist of a broad spectrum of materials such as fibres of varying length, granulates, particles or a combination of these (Netravali & Pastore 2014).

In contrast to conventional metals or ceramics, the structural behaviour of composites is in most cases anisotropic (directional), due to their internal fibre direction, resulting in distinct behaviours for different load-cases (US Department of Energy 2015).

Various materials occur in their natural form as composites. Wood, perhaps one of the most relevant examples in the context of architecture, consists of cellulose fibres embedded in a lignin matrix (Hull & Clyne 1996). Elaborate wood constructions, such as Neolithic longhouses (Figure 11), measuring up to 7m in width and 45m in length which date back to 5000 BC

Neolithic Longhouse structural layers visualisation:

http-//www.archaeo3d.com/en/lide-z-dlouhych-domu/lide-z-dlouhych-domu/lide-z-dlouhych-domu/.jpg

(Image redacted for copyright reasons)

Figure 11 Neolithic longhouse construction process rendering (Petr Vavrecka)

(Kvetina & Hrncír 2013), suggest that the use and precise knowledge of the properties of this versatile natural composite is deeply ingrained in both human and architectural culture.

One of the oldest engineered composites in the architectural context is possibly the mixture of mud or clay with straw or other natural fibres to generate building materials, such as adobe bricks (Tarlochan 2013). The oldest documentation of this process can be found in Egyptian drawings dating back to 1450 BC. However, it can be assumed that this technique was known well before this date: the oldest bricks that have been found date back to 8300 BC (Campbell 2003).

In the southern marshes of Iraq the very distinct building typology of mudhifs (Figure 12), which still exists today, originated over 5000 years ago (Broadbent & Brebbia 2008). This building technique uses reed to construct arches as a main load-bearing element for dwellings. Large elements are generated by bundling multiple strands of reed, which are gradually bent into the desired shape to form load-bearing structural elements.

In general, reed is usually not considered a suitable material for loadbearing elements, due to its flexibility and low compressive strength, but by bundling multiple strands and by using it in a specific active structural bending setup which utilises its flexibility, a comparably high-performing and economic composite structure emerges. This distinctive construction technique can be understood as one of the first examples of structural architectural composite beams (Lienhard et al. 2013).

In contrast to stone architecture, these natural materials are prone to decompose in a comparably short time, due to their organic origin, and only a few examples and clues, found either through excavation, building tradition or ancient drawings, allow us to trace back our ancestral material knowledge. History suggests that our architectural heritage was much richer, in terms of the knowledge and use of composite materials for construction, than is currently assumed.

Mudhif construction process:

http://whc.unesco.org/include/tool_image.cfm?id=142111

(Image redacted for copyright reasons)

Figure 12 Mudhif construction in Iraq. Bundling individual reed branches to manufacture a beam

Mudhif interior:

https://www.prmprints.com/image/422021/interior-of-a-mudhif

(Image redacted for copyright reasons)

Figure 13 Mudhif interior

B. Synthetic

Initially, the range of composites available for design and construction depended on naturally occurring materials such as natural fibres of various origins combined with additives and binders based on natural resins, rubber, bituminous substances or plant oils. This fundamentally changed after 1860, when Adolf von Baeyer laid the theoretical foundations for the development of modern plastics. From this date onwards, the family of petrochemically-derived synthetic plastics and resins grew steadily and changed the way modern society consumes, produces and lives. This new class of materials offered high-performing and cost-efficient synthetic fibres and resins.

This illustrates a pivotal point in architectural history which enabled designing with an entirely new and synthetic material created wholly in the laboratories of chemical companies. The field of synthetic plastics and fibres generated a entirely new domain within the field of composites, creating continuously expanding and almost inexhaustible possibilities for new and potential material combinations.

In the 1930s the field of composites experienced another fundamental leap when glass fibre was commercialised, which, in combination with the advances in resin technology, enabled the first glass-fibre reinforced polymers (GFRP). Initial applications were reserved for military, automotive and aerospace use before the material gradually permeated the field of design and architecture in the 1950s and 1960s. Pivotal designs like the Eames DAR (Dining Armchair Rod-base) chair utilised the characteristics of the new material and manufacturing techniques to mass-produce complex shapes material- and cost-efficiently.

The use of these materials within construction and architecture started with applications for military radar domes in 1954. Buckminster Fuller, for example, engineered a Geodesic GFRP radar dome based on a repetitive hexagonal pattern which promised the efficient use of materials and fast construction.

Two years later, in 1956, the architects Ionel Schein, Yves Magnant and René Coulon envisioned the “Maison tout en plastique” – the all-plastic house, one of the first prototypes for a residential building made from GFRP (Figure 14). It consisted of curved sandwich panels of GFRP and was built in France in collaboration with the chemical company Camus et Cie (Engelsmann et al. 2010). This specific example was still mostly determined by an approach which can be described as “panelisation”. Derived from a building industry which relies on modular systems to generate larger assemblies, the “snail shell house” also relies on mostly flat panels made of GFRP composite materials, without exploiting the full geometrical and

Maison tout en plastique, model top view:

http://www.frac-centre.fr/_en/art-and-architecture-collection/schein-ionel/maison-tout-plastiques-salon-des-arts-menagers-paris-317.html?authID=171&ensembleID=554

(Image redacted for copyright reasons)

Figure 14 "Maison tout en plastique", model, Ionel Schein, 1956

Maison tout en plastique, model front view:

http://www.frac-centre.fr/_en/art-and-architecture-collection/schein-ionel/maison-tout-plastiques-salon-des-arts-menagers-paris-317.html?authID=171&ensembleID=554

(Image redacted for copyright reasons)

Figure 15 "Maison tout en plastique",, model top view, Ionel Schein, 1956 expressive potential. Althought the material is inherently different in its manufacture and performance, its tectonic utilisation these cases is identical to conventional panelised materials.

1957 the chemical company Monsanto sponsored a construction research project, in collaboration with the Massachusetts Institute of Technology (MIT), which resulted in the manufacturing of their House of the Future (Figure 16). In contrast to Schein, Magnant and Coulon's model, this design consisted of modular large-scale pre-fabricated GFRP elements which fully exploited the morphological potential of the material while at the same time providing structural integrity and thermal insulation, due to the use of polyurethane foam as internal layer of the sandwich structure (Dietz 1965).

These two examples illustrate how the exploration of this new material in the architectural context is directly connected to manufacturing research and material engineering. Both projects were supported and developed in collaboration with chemical companies and/or research institutes. Whereas conventionally building materials are such as steel, concrete or bricks are usually semi-finished products with well-known properties and specific tools for construction, new material systems and processes call for a different approach. A close cooperation between research and development and designers is crucial for exploring the demands and potentials of new technology, thus fostering interdisciplinary synergies. The projects described laid the foundations for more advanced work in the 1960s, such as Matti Suuronen's Futuro House (1968), or Buckminster Fuller's Fly's Eye Dome (1975) (Figure 17) (Lienhard et al. 2013).

Many of these iconic and visionary projects were designed for mass production, but their futuristic design did not resonate with the prevailing public notion of architecture and design. In addition, the oil crisis of the 1970 lead to an increase in production costs, inhibiting the number of projects appearing in the mass market (Engelsmann et al. 2010). The costly and labour-intensive manufacturing process, which demands trained specialists, was another drawback that hindered the breakthrough in the building industry (Bucquoye & Beukers 2002).

Although most of these projects did not receive the anticipated acceptance, they are still considered influential because of their material-driven design process.

In the 1960s, carbon fibres were developed. This specific class of fibre, consisting almost entirely of carbon, delivers unprecedented properties. Due to its distinct ordered hexagonal atomic structure it outperforms other synthetic fibres by far, being five times lighter than steel and delivering more rigidity (Bucquoye & Beukers 2002). Although carbon fibre promised unrivalled properties, it remained a niche product, reserved for aerospace and military applications due to its high price and complex production process, until the late twentieth century. Mass production and new manufacturing methods have allowed the material to

House of the Future, front view

https://craftofcoding.files.wordpress.com/2015/07/monsanto1957.jpg

(Image redacted for copyright reasons)

Figure 16 House of the Future concept by MIT and Monsanto

Fly's Eye Dome, front view

https://www.archdaily.com/343036/buckminster-fullers-50-foot-flys-eye-dome-to-be-restored/513e5083b3fc4b530d000003-buckminster-fullers-50-foot-flys-eye-dome-to-be-restored-photo

(Image redacted for copyright reasons)

Figure 17 Buckminster Fuller, Fly's Eye Dome, 1975 gradually permeate almost every industry where weight and performance matter. More recently, the material has also found its way into the architectural domain.

C. Automation

Even though the production technology of composite materials has advanced significantly since the early 1960s, the process is mostly dependent on mould-based manufacturing techniques and intensive human labour. However, the manual fabrication is very different from other manufacturing techniques. During the process a soft textile in the form of sheets of fabric, strips or individual fibres is positioned into the desired shape and impregnated with a resin which gradually hardens it. This gradual material transition from soft to hard allows interaction with the material in new ways, such as incorporating specific layering patterns or inlays to allow for anisotropic (directional) behaviour. In comparison to the classic construction methods using materials like steel or aluminium, the form-giving is usually achieved by pressing, welding or casting, which generates a homogeneous material. Manufacturing with wood, a naturally occurring composite material, initially employs subtractive fabrication strategies entailing shaping through gradual material removal.

While the manufacture of metals or the methods of working with wood have been developed over centuries, the relatively new development of manufacturing polymer-bound composites comprises a unique additive process which is still in development, and its full potential for architecture and design have not yet been fully exploited.

The fabrication of composite materials was for a long time bound to the production of panelised or continuous large-scale elements for industrial applications such as wind turbines.

The aerospace industry, increasingly using composite parts for aeroplanes, is one of the main drivers for manufacturing innovation in the field. Due to their high structural performance, corrosion resistance and lightweight characteristics, composites promise increased performance through weight reduction, material efficiency and low maintenance (Chawla 2012).
However, the accuracy, speed and cost of manual assembly do not satisfy the demands of the industry. Therefore, an increased effort has been made in recent decades to automatize their manufacture employing robotic manufacturing.

Three main strategies are commonly used to apply the impregnated fibres – spraying, layup and winding (Åström 1997). The geometry of the mould, as well as the structural demands, thus determine the production method. Anticlastic geometries are usually manufactured by spraying or layup of the fibres. The spraying process offers a rapid method, which results, however, in a unidirectional fibre distribution, whereas the automated layup is more time-consuming but offers precise control over fibre direction and layering. Robotic Composite

Robotic layup:

http://www.automateddynamics.com/automation-equipment

(Image redacted for copyright reasons)

Figure 18 Robotic automated composite layup on a prefabricated mandrel

Automated carbon fibre winding:

https://www.connova.com/en/loesungen/composite-bauteile/fertigung/wickeltechnologie/

(Image redacted for copyright reasons)

Figure 19 Composite winding process: the continuous fibre is being wound onto a synclastic mandrel winding is usually deployed for synclastic geometries using a rotating mould, known as mandrel (La Magna et al. 2014).

The rise of robotic automation has also permeated the field of textiles and architecture. Whereas textile machinery is usually bound to a very specific task which is repetitively executed by mechanical means, robotic arms allow for a constant reiteration of their task through recoding and end-effector design.

Theoretical projects such as Peter Testa's Carbon Tower (2001) (Figure 20) depart from the classic mould-based fabrication method, instead involving on-site robotic manufacturing of carbon composite structures (Testa & Devyn 2006). Although the project was not realised, it can be understood as one of the first examples of this new mode of construction for architectural design.

Rather than being a modular assembly of individual parts, the Carbon Tower concept envisions a on-site fabrication method comprised of robotic carbon fibre winding (McQuaid 2006). This example shows that not only is the material itself a driver for developing new design strategies; new modes of fabrication, such as the emergent field of robotics, with its distinct aesthetic of performative manufacturing, can also be embedded in the architecture.

The ICD/ITKE Research Pavilions[5] by the Institute for Computational Design and Construction at the University of Stuttgart combine computational design methods and the advanced robotic fabrication techniques derived from the aviation industry, with the use of state-of-the art carbon and glass fibre systems (Knippers & Koslowski 2017) (Figure 22). While the raw materials and toolsets for these particular projects have been established and explored for many decades in fields like aeronautics (fibre lamination technology) and the car industry (robotics), as well as in the field of design and engineering (computational design and simulation), the ICD/ITKE projects demonstrate that advances in design are dependent not merely on material innovation but equally on interdisciplinary exchange and innovative design methods connecting different fields of knowledge, thus fostering radically new approaches. In this case, not only does the manufacturing method differ inherently from conventional architectural construction; concomitantly the distinctly textile character of the structure is expressed through the process.

The ICD/ITKE Research Pavilions illustrate the versatility and expressive potential of the technology in the context of architectural design. The fundamental fibre deposition system remains almost unaltered compared to industrial systems; the design methodology, however, exploits the full geometrical potential of the robotic system and the continuous manufacturing

5 Appendix C provides further details for ICD/ITKE Research Pavilion 13/14 and 16/17

Carbon Tower, front view:

https://cargocollective.com/kyhox/PETER-TESTA

(Image redacted for copyright reasons)

Figure 20 Carbon Tower, Testa & Weiser, 2001

Carbon Tower, front view:

https://montrealgazette.com/entertainment/arts/visual-arts-modern-design-found-beauty-in-utility-thank-you-technology

(Image redacted for copyright reasons)

Figure 21 Carbon Tower, Testa & Weiser, 2001 principle while generating a distinct textile morphology. While conventional composites usually appear as one monolithic and continuous material (panelization), the distinct mode of manufacturing in the ICD/ITKE project allows for very distinct fibrous tectonics in which individual fibres are apparent throughout the individual segments.

2.5. Discussion

Advances in composite materials are largely dependent on innovation in three main fields: fibres, matrix materials and manufacturing methods. These fields originated as three distinct disciplines within the field of manufacturing and material research, and are still operating as independent entities in the technical textile and polymer industries, as well as in robotics and automation technology. The field of composites bridges these fields, and thus profits from developments in each individual discipline.

The case studies illustrate how fibre-based composites can be manufactured for complex performance, such as directional, isotropic or anisotropic behaviour. The process of their manufacture can directly be embedded into the design process to foster these advantages for unique structural solutions.

The distinct textile tectonics and complex structures are fostered through a relatively simple principle which is based on the emergent behaviour of individual fibres in a specific array and direction, embedded in a rigid matrix. By pairing this principle with state-of-the-art manufacturing and design methods, novel aesthetics emerge.

The distinct feature of textile-based composites is their material transition, which allows for a soft manufacturing during which the individual fibres behave in a textile-like way. During this stage the manufacture of composite winding techniques is based on a tensile system. In the specific fabrication processes approach applied in the ICD/ITKE projects, the robotic winding establishes a tensile system through the winding of individual fibres between the nodes. During the curing process their state changes from one that is soft and mouldable to a rigid system with global behaviour which can, besides tensile forces, withstand compressive forces.

Robotic coreless winding (ICD/ITKE)

http://www.achimmenges.net/?p=5713

(Image redacted for copyright reasons)

Figure 22 Coreless composite winding process for the ICD/ITKE Research Pavilion 2013/14 © ICD/ITKE

Elytra Beetle micro-structures

http://www.giuliobrugnaro.com/icditke-pavilion-2013-2014/l8fmva4srkpvzzxajtlu87ue48flxc

(Image redacted for copyright reasons)

Figure 23 Biomimetic investigation of Elytra beetle for fibre distribution © Dr.Thomas van de Kamp, Prof. Dr. Hartmut Greven

The ICD/ITKE Pavilions illustrate impressively the potential of integrated composite manufacturing for the architectural domain. The high-tech materials deployed for the project consist of carbon and glass fibre impregnated with high-performance resins. While they deliver unprecedented performance in relation to their structural property, light weight and durability, their production demands large amounts of energy and is heavily dependent on petrochemical resources (Netravali & Pastore 2014). Additionally, there are major challenges in terms of their recycling (US Department of Energy 2015).[6]

While the projects described above contribute to the tectonics discourse and the advancement of design and manufacturing systems, the performativity of the material, apart from its outstanding structural characteristics, is rather limited. Although the project grounds its form-finding strategy in a biomimetic approach (Figure 23), its materialisation remains in the domain of synthetic and static materiality. In order to holistically approach new fibrous tectonics inspired by biological systems, we will have to reframe the notion of performance within the domain of architecture.

2.6. The ecology of performance

Performance in the context of composites is strongly connoted by the notion of technical performance drawn from the domain of mechanical engineering. NASA (2013) defines the term 'technical performance' as:

The set of critical or key performance parameters that are monitored by comparing the current actual achievement of the parameters with that planned at the current time and on future dates. (NASA 2013, p.10)

The technical notion of performance is concerned with distinct quantitative parameters providing information about structural loads, durability or the fatigue effects of materials. Based on these performative criteria, materials are designed or selected to match, or to be analysed in accordance with, a set of distinct parameters. However, this quantitative lens focuses on and evaluates only one specific moment and situation in the life cycle of a material. While those engineering protocols enable high efficiency and reliability, they render a rather autistic material concept. Although technical performance is crucial when it comes to an architectural application of composites, their distinct qualitative features are similarly relevant. Haptic, visual, interactive and expressive qualities are characteristics that architectural materials have to account and perform for. Furthermore, by being embedded in an architectural context, they are

6 Further information on the sustainability of carbon and glass-fibre based composites can be found in appendix D

2013/14 Research Pavillion

https://icd.uni-stuttgart.de/?p=11187

(Image redacted for copyright reasons)

Figure 24 ICD/ITKE Research Pavilion (2013/14) © ICD/ITKE

2013/14 Research Pavillion, detail

http://www.achimmenges.net/?p=5713

(Image redacted for copyright reasons)

Figure 25 ICD/ITKE research Pavillion (2013/14), detail fibrous morphology © Roland Halbe innately entangled within the social, environmental and aesthetic discourse. These parameters leave the realm of the binary and measurable, and thus call for an extension of the notion of performance for architectural composites.

The reconsideration of the notion of performance to features such as adaptability or responsiveness extends the relevance of time and interaction beyond mere considerations of wear and durability. Such an understanding of performativity moves away from target-focused engineering models and positions architectural composites in relation to their environment, thus enabling interactive and responsive qualities.

Moving away from a target-driven model towards a material and context-focused thinking model blurs the boundaries of a material's performative scope. Conventionally, the field of engineering defines the specific application, a materials "lifetime" when it will be decommissioned. This perspective, however, merely accounts for the full life-cycle of a material.

To account for a holistic understanding of material performance, time-based transitionary states similarly play a role (Tibbits 2017). These states include manufacturing, interaction and decay processes (Benjamin 2017). Whereas decay processes occur naturally on site, the manufacture of materials or composites is usually locally and chronologically separate from their place of application.

An in-situ manufacture can thus not only involve less transportation effort but can also contribute to a new design paradigm in which performative construction processes are inscribed within materials or are an integral part of the design strategy.

Shifting away form a man-made engineering system, biology offers an inherently different approach. A tree, as one example of a natural system actively generating a composite, directs the generation of structure according to external parameters and available resources. In this case, the (biological) system generating the structure resembles the structure. This intriguing parity and relation between maker and result offers a poetic blueprint for future material systems. At the same time it offers a different tectonic concept which is in constant flux and reiterates itself according to external parameters.

The following paragraph discusses how performative features such as adaptability and responsiveness might demand a reconsideration of the conventional tectonic paradigm within the architectural domain.

2.7. Tectonic framework

> When a structural concept has found its implementation through construction, the visual result will affect us through certain expressive qualities which clearly have something to do with the play of forces and corresponding arrangement of parts in the building, yet cannot be described in terms of construction and structure alone. For these qualities, which are expressive of a relation of form and force, the term tectonic should be reserved. E. Sekler (cited in Kepes 1965, p.89)

Eduard Sekler understands tectonics as the expressive manifestation of the translation process of a structural principle into the physical domain (Frampton 1995). This understanding also alludes to the importance of tools, materials and processes as the facilitators for achieving a distinct expressive quality.

Schumacher (2017), in this context, understands the tools (digital and physical) and material properties as a central element for extending the repertoire of tectonic expressions. He calls for a shift within parametric design towards what he calls tectonism. Arguing for the utilisation of modern CAD/CAM- (Computer aided Design/Manufacturing) driven design processes to parametrically inform the generation of tectonic expression, his aim is to prevent parametric design from "descending into arbitrary form invention" (Ibid, p.109). The strategy he outlines is grounded in computational form-finding, based on real-world physics and the expressive potential of new CAM manufacturing techniques.

In the light of recent technological advances and form-finding principles, Nilsson (2007) argues for a new taxonomy of tectonic principles. His argument is based on an investigation into architectural projects incorporating novel design strategies, such as the use of computer science, biology and engineering. He proposes algorithmic tectonics, fluid form-finding tectonics and technological swarm tectonics as a taxonomic framework for new tectonic expressions.

Tectonics, however, are generally perceived as a static and final design outcome as a result of a specific design process or materiality (Schumacher 2017), or a distinct approach to technology or philosophy (Nilsson 2007). This understanding implies a clear chronological and conceptual division between construction and tectonics. Construction can be understood as a time-based and ephemeral translation and formation process between concept and reality, which is generally perceived as a mere means of fabrication and thus not concerned with aesthetics.

Tectonics, on the other hand, is deeply rooted in an aesthetic discourse and presents itself as a static, atemporal statement without a transformational character.

The research thus interrogates two specific features of tectonics:

A. Time-based (transitional tectonics)

The research operates within the fields of construction and tectonics, while proposing a conceptual synchronicity of both. Embedding an assembly system as an integral and permanent part of a construction heightens the process of construction towards becoming an expressive tectonic feature. Concomitantly, the notion of tectonics becomes time-based and transitional, suggesting a new breed of transitional tectonics.

B. Relational and dynamic (reciprocal tectonics)

Tectonic expression materialises as a distinct design response in accordance with a structural system. The design, originating from a qualitative perspective, is constructed around a set of physical quantitative parameters such as topology, material, self-weight and gravity (Frampton 1995). Because these parameters are a constant they result in a static tectonic expression.
The opportunity to incorporate dissipative and dynamic parameters calls for a reconsideration of the prevailing static tectonic expression. Projects such as HygroScope: Meteorosensitive Morphology (Reichert et al. 2015) incorporated environmentally reactive and dynamic elements which actively change the performance of the building material. Cruz & Beckett (2016) deployed a bio-active cryptogamic layer on a cement-based substructure. This means of dynamic adaptation and responsiveness, however, profoundly elevating the aesthetic and functionality of the building elements present secondary structures, do not permeate to the primary structural tectonic level.

Natural structures emerge through an exchange of energy and nutrients with the environment. The underlying principle of natural morphogenesis can be found in biological metabolism, which will be discussed in detail in the following section. Biological metabolic systems enable characteristics such as self-regeneration, self-repair and emergent intelligence (Luisi 2007) and provide a systemic blueprint for the projects discussed in this research.

Harnessing the reciprocal relationship with the environment and the dissipative state (Maturana & Varela 1980) of biological systems on a structural and conceptual level, or environmentally reactive and responsive materials systems, could lead to novel reciprocal tectonics.

The research focuses on investigating potential design approaches for transitional and reciprocal tectonics in the domain of fibre-based composite structures.

3. Biology I: Metabolism

3.1. Biology, performance and tectonics

As outlined previously, the performativity of biological systems and engineering materials are subordinate to different domains of reference. While biological organisms operate innately as dissipative, adaptive and dynamic systems (Luisi 2007), the prevailing performativity of architectural materials remains static and constant.

While Chapter 1 was concerned with fibrous tectonics and their manufacture, the second introductory chapter aims to outline the distinct relationship between the field of modern biology and tectonic culture.

The science of biology as a discrete discipline is relatively young (compared to disciplines such as mathematics or philosophy), and was introduced by the naturalist Jean-Baptiste Lamarck around 1802 as the "new science of life", which "emphasised the communality of the forms of animal and plant life and stressed the distinctiveness to the non-living" (Keller 2002, p.15). Needless to say, studies of plant morphology and animal and human physiognomy had been undertaken before the emergence of biology as a discrete field of science. Similarly, there are countless historic references to the ways in which these geometrical and formal studies inspired and were translated into the tectonic realm (Rykwert 1972; Frampton 1995; Rykwert 1998; Steadman 2008). This historic aesthetic and tectonic engagement with biology models the basis for, and a provides sustained inspiration and reference for, the modern architecture-biology discourse. However, for reasons of conciseness, the following chapters will focus on modern biology and biotechnology and its impact on the tectonic domain.

Myriad examples can be found of the ways in which modern biology inspired new tectonic expression on a material, as well as on a functional, level. The following chapters will only be able to present a few of these to outline the relevant framework for the research.

> "...in biology, material is expensive but shape is cheap. As of today the opposite is true in the case of technology." (Vincent 2009, p.78).

The forms and shapes which emerge from biological activity have presented a great source of formal inspiration (Thompson 1917). In parallel with technological advances of observation and examination tools, such as scanning electron microscopy, our knowledge of biologically derived materials is advancing.

The fundamental work and contribution of Frei Otto and Buckminster Fuller in this context needs no further introduction (Otto 1982; Fuller & Applewhite 1975). These designers revolutionised how we think about structure, construction materials and scale based on, among others, through inter-scalar observation of biological structures.

Vincent (2009), cited earlier, outlines one of the fundamental objectives of a biomorphic approach. Here, the general paradigm is to deduct, from a biological paragon, distinctive formal, structural and material distribution features, in an inter-scalar approach. Shells of diverse maritime organisms, as one example, present through their specific global geometry very efficient and optimised structures for a specific structural demand (Figure 27). Similarly, on a micro and nano level the internal structure is comprised of a highly efficient composite. This specific composite emerges through bio-mineralisation (which will be discussed in detail at a later stage), forming mineralic plate-like micro layers (Zolotovsky 2017) (Figure 28). This interdependent and hierarchical material organisation is highly material efficient but, however, merely manufacturable at scale even with advanced means of fabrication (Vincent 2009; Zolotovsky 2017).

The ICD/ITKE pavilions outlined in the previous chapter tackle the issue of manufacturability through upscaling. Their design and form-finding principles are based on microstructures found in biological systems, which then are scaled up to enable manufacturing. Although this leads to very expressive and efficient structures, this step intermingles the logic of the structural hierarchies and dependencies and creates an incoherence in relation to their biological original paragon. Simultaneously, the microstructural constitution is not accounted for. The different modes of structure-generation – biological and man-made – obviously present themselves as inherently distinctive (Figure 26). These architectural and design projects exemplify the

Biomimetic Patterns in Architectural Design (Vincent 2009), infographic p.76

Figure 26 Differentiation between natural and manmade generation of structure (Vincent 2009)

Abalone shell

http://www.seaurchindesign.com.au/?product=tasmanian-abalone-shell-large

(Image redacted for copyright reasons)

Figure 27 Abalone shell macro structure

Abalone nacre

http://animalia-life.club/other/abalone-shell-structure.html

(Image redacted for copyright reasons)

Figure 28 Abalone shell (nacre) micro structure negotiation process, compromises and abstraction needed to successfully apply a biomimetic logic to the tectonic domain. Concomitantly, it also presents the multiple opportunities for material design and tectonics.

These examples show that biology can inform tectonic systems on multiple levels. The exact methods of biomimetics, bionics, biomimicry or bio-inspired design might differ in detail; however, they share the main objective, which is to translate systems, form and shape, derived from the investigation of biological systems in different domains (Vincent 2009; Knippers & Speck 2012; Pohl & Nachtigall 2015). Deducting certain design principles presupposes finding a suitable paragon to examine. Once located, the method generates knowledge from an investigation into biological systems whose behaviour, form and material developed over millions of years through constant reiterations (Darwin 1859).

3.2. Biological metabolism

"The living is a factory that remakes itself from within" (Luisi 2007, p.129)

While biological evolution constantly iterates form, structure and behaviour over time, the main driver for this process has remained mostly unchanged. This intrinsic biological process, underlying millions of years of biological development and iteration, is understood as metabolism (Boden 2000). Metabolism functions as the main cellular process generating energy and translating matter into biological structure (Luisi 2007). It is understood as the lowest common denominator of every living organism; hence it "locates life on earth" (Boden 1999, p.234). It is a biochemical process by which, through a distinctive intake of chemicals and their processing within a biological cell, energy is generated, which translates into emergent characteristics such as growth or (self)-reproduction (Boden 1999). The complex biochemical processes occurring during biological metabolism can be categorised in three main metabolic pathways – catabolic, anabolic and amphibolic (Voet et al. 2013). Through the catabolic pathway, chemical energy is generated by processing energy-rich sources such as carbohydrates, fats and proteins. The anabolic pathway utilises energy to assemble macromolecules, such as nucleic acids, proteins or polysaccharides, from smaller molecules. The amphibolic pathway, dependent on demand and resources, can be either anabolic or catabolic (Voet et al. 2013).

A permanent exchange of molecules, matter and energy takes place to maintain homeostasis – a state of optimal conditions through a constant dynamic exchange and regulation. Metabolism "involves the autonomous use of matter and energy in building, growing, developing and maintaining the bodily fabric of a living thing" (Boden 1999, p.237), which provides the basis for the evolutionary principle. The multiplicities of these micro-exchanges enable the emergent system of intelligent biological life which adapted and responded to environmental conditions, resource availability and structural interdependencies. A shell, which was part of the earlier example, emerged from the distinctive metabolic process of the crustacean. Although the shell is derived from one single organism, it has inscribed millions of years of evolution over countless previous generations.

The example of the shell in the biomimetic context exemplifies one branch of the relationship we have with biology which is distinguished by an observational and deductive character. This involves an abstraction and translation of systems and principles from biology in other domains.

The field of modern biomimetics, then, locates and deducts single behavioural-, functional or material features derived from a biological system. The organism from which the feature is derived is in this respect not necessarily understood holistically as a living entity. In relation to the shell structure, it is not important to understand the whole behaviour or metabolism of the crustacean: it is coherent with the logic of a material sample.

The following chapter will investigate an approach in which the material expressions of the organism are not the focus of interest, but rather the underlying metabolic principle they emerge from.

4. The Duck

4.1. Automaton – phenomenon and analogy

Biology, as outlined in the previous chapter presents a plethora of inspiration on a formal and structural level. Similarly, the unique character of "aliveness" has inspired artists, engineers and designers equally throughout the centuries. Characteristics of life, such as cognition, intelligence, perception, evolution and reproduction, can be understood as emergent properties of biological metabolism. Similar to the practice of biomimetics, which was explained earlier, designers, engineers, philosophers and architects have found inspiration in the specific metabolic paragon of biology and the organism as a self-sustaining, self-reproducing unity (Boden 2000; Steadman 2008).

Steadman (2008, p.4) suggests "the idea of "wholeness", "coherence", "correlation" and "integration, used to express the organized relationship between the parts of the biological organism, can be applied to describe similar qualities in the well-designed artefact", continuing by proposing that "some of the principal concepts of modern biological philosophy – of evolution, of morphology, of classification of the behavior of dynamic systems, of the transmission of information through hereditary processes – all these have, at the abstract, formal level, a great deal to offer those infant sciences which are devoted to the study of man-made objects and their design." (Ibid 2008, p.6)

The degree of abstraction in connection with materialisation is therefore of significant importance. Throughout the history of philosophy and technology these analogies and metaphors have facilitated a vehicle to scrutinise, explore and extend the idea of "aliveness" and the functionality of life.

The imitation of "life-like" features through mechanical means has a long history. Some of the earliest documentations of an human analogue automaton "with death-defying" (it can be presumed that during their transmission some dramaturgical ornamentation occurred) features date back to 150BC (Wood 2002). However, these mechanistic approximations of life prevailed and reverberated in the Cartesian understanding of biological organisms. Descartes' theory suggested that "all that was natural was also mechanical, and consequently any differences between animals and man-made artifacts were purely quantitative rather than qualitative" (Nicholson 2014, p.163). This tradition of mechanicism, which proposes a deterministic view of nature, has its roots in the natural philosophy of Galileo, Descartes, Gassendi and Boyle, and emerged during the scientific revolution (Nicholson 2012). Descartes' understood the body as a "moving machine", which contrasts with the notion of the body as a "self-moving machine", suggested by La Mettrie, in his L'Homme machine (1748). He describes the human as a "self-winding machine, a living representation of perpetual motion." (Wood 2002, p.12).

The early understanding of biological systems in a mechanistic tradition triggered the design of myriad sometimes questionable automata in the quest to engineer and mechanise the dissected features of life and, through a combination of these, pursue the creation of "artificial life" (Reichle 2009).

Around a century after Descartes suggested his mechanistic concept of the body, Jacques de Vaucanson created his anthropomorphic flute-player which, through mechanical means, reenacts the bodily choreography of a human playing the flute. The work of Vaucanson was considered highly provocative: it suggested the creation of a direct link between man and machine and embodied the secular perception of the emerging European Enlightenment (Wood 2002). The scope of Vaucanson's work, in a way "philosophical experiments" (Riskin 2003, p.601) more than mechanical ones, concerns the discourse of anthropomorphism, sociological or secular politics, however, the aim here is to focus on the distinct position of his work in relation to biological metabolism.

In 1739 Vaucanson exhibited a mechanical analogy of a duck, coined *Canard Digérateur* - the digesting duck- (Figure 29) which, in his own words, "stretches out its Neck to take Corn out of your Hand; it swallows it, digests it, and discharges it digested by the usual Passage." (Riskin 2003, p.599). This functionality alludes to an inherently different conceptualisation from that of the flute player described above. With the duck, Vaucanson offers an analogy which does not concern the emergent intelligence or dexterity of living organisms (as seen in work of Pierre Jaquet-Droz (his writer, draughtsman, lady musician) but to the underlying processual, metabolic character of bodily functionality (Figure 30). He illustrates a material transformation which occurs between two systems – organic matter (food) and mechanical "artificial life" (duck) – as analogous to the biological digestion system, which resembles part of a metabolic process.[7] However, these two systems are not compatible: it was impossible for the mechanical system to draw energy from the chemical/organic food source provided, even though certain digestive agents are utilised to illustrate the process (Wood 2002). The missing systemic interface (allowing the translation of chemical into kinetic energy) is substituted by a human input of kinetic energy, similar to clockwork. This contrasts with a biological organism which maintains itself through exchange with its immediate environment (Luisi 2007).

7 In this context one should similarly acknowledge and credit the performative and visionary artistic quality of a gold-plated mechanical duck defecating on an ornamental pedestal, accompanied by a mechanical flute player and drummer, in the Grand Salon of the Hotel de Longueville.(Figure 29)

Illustration of Vaucansons Duck in exhibition setting

https://exhibits.museogalileo.it/nexus/enex.php?c[]=49102

(Image redacted for copyright reasons)

Figure 29 Vaucansons Duck on display with flute player and drummer automatons

Vaucanson states that he does “not pretend to offer this digestion as a perfect digestion. Capable of producing blood and nutritional elements for the animals continuing health” (Wood 2002, p.26), alluding to his awareness of digestion being a mere metaphor for its biological function. Although Vaucanson’s duck (Figure 31) could be seen merely as a rather formal and overly reductionistic metaphor of its biological, living paragon, it is, in the historical context of early mechanicism (Nicholson 2012), a unique historic reference of a mechanical engagement with the processual, metabolic character of a biological system through design, engineering and construction.

After his success with his automatons, Vaucanson was approached by Louis XV, after he saw Vaucanson’s duck, to reproduce a human automaton with a fully functional, metabolising mechanical body, to study the phenomenon of blood circulation (Wood 2002; Reichle 2009). This project, however, was never realised, due to its complexity. It was long after the heyday of the physical automaton that, around 150 years after Vaucanson’s duck, the biochemical fundamentals for metabolism of living organisms were outlined, revealing the mechanisms for nature’s distinctive performativity. Although the conceptions, tools and methods of modern biology have fundamentally advanced since the scientific revolution, the repercussions of the mechanical analogy are still present on a terminological and semantic level. The analogy of a cell as a machine and its constituents (e.g. mitochondria = power generator) as functional parts, commonly used in modern biology connotes curious semantic parallels with Descartes’ and La Mettrie’s theories (Nicholson 2014; Ellis et al. 2011; Voet et al. 2013).

The modern notion of metabolism in biology, as a dynamic state of exchange of matter and energy, similarly inspired the field of architecture on a systemic level. While Vaucanson’s work operated within a materialistic domain and a scalar and formal similitude to/coherence with its biological paragon, the Metabolism architectural movement in the 1970/80s presented a very extensive approach which was concerned with large-scale systems, material flows and their transformation over time while abandoning scalar (biological) dependencies.

Kisho Kurokawa (1977 p.27), part of the Metabolist group, stated that that the group used the biological term because they believed that “design and technology should denote human vitality. We do not believe that metabolism [in architecture] indicates only acceptance of a natural, historical process, but we are trying to encourage the active metabolic development of our society through our processes”. They operate with a model in which “human society must be regarded as one part of a continuous natural entity that includes all animals and plants”, and suggested that “technology is an extension of humanity” which “contrasts with the Western belief that modernization is a repetition of a conflict between technology and humanity”(Ibid, p. 27). “The Metabolist movement conceived the city as a living organism undergoing a process

Illustration of Vaucansons Duck

https://upload.wikimedia.org/wikipedia/commons/7/75/Duck_of_Vaucanson.jpg

(Image redacted for copyright reasons)

Figure 30 Conceptual artistic drawing of the Duck (not by Vaucanson)

Photograph of mechanical automaton:

https://www.outerplaces.com/science/item/4919-the-origins-of-the-modern-robot-a-wooden-bird-from-400-bc-leonardos-columbine-and-a-deficating-duck

(Image redacted for copyright reasons)

Figure 31 Photography of the damaged automaton after damaged by a fire of renewal and obsolesces, experiencing cyclical transformations, turgidities and declines comparable to those of organic tissue." (Kurokawa 1988, p.8). This metaphor was applied to inter-scalar dependencies between building elements, housing units, structural systems and the scale of the city, even including speculative projects on the ocean.

Extending the analogy of biological systems beyond materiality calls for a change of terminology. Metabolism in this context might be the wrong term to use, as it describes a biochemical process within a physical space (Boden 2000).

The term autopoiesis, however, coined by Maturana & Varela (1980), similarly strongly connoting physical space, operates on a systemic level, not as a physical process, and therefore can potentially be applied to different domains, even outside the physical world (Buchinger 2006). Boden (2000, p.123) states that "Metabolism is not part of the definition of autopoiesis

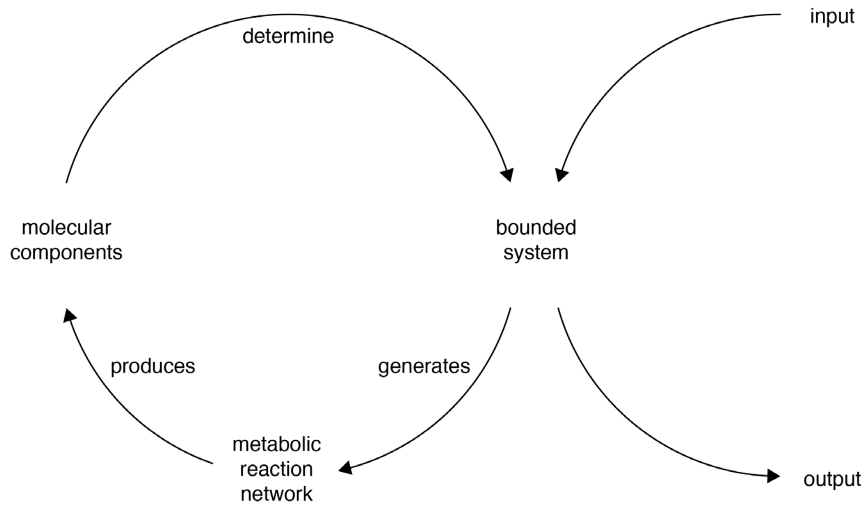


Figure 32 Autopoietic unit diagram after Luisi (2007)

as such, since autopoiesis is a more general concept. But it is constitutive of its material structure when autopoiesis is realized as a living thing."

Autopoiesis is understood as a "phenomenological analysis of life as it is on Earth" (Luisi 2007, p.155). It can be described as the common denominator of the various existing forms of life, and describes the intrinsic self-generation of cellular life. Every cell-based system occurring on earth can considered a "molecular autopoietic system" (Maturana & Varela 1980). The notion of autopoiesis stands as one of the major fundaments of the systems view of biology, and enables the differentiation of living systems from inanimate matter (Luisi 2007).[8]

Rather than describing the individual biochemical reactions and complex processes which vary with each cell system, the concept of autopoiesis offers a systems approach inherent to every living organism. Through this seemingly simple concept, the three basic modes of a cell are maintained – homeostasis, growth/reproduction and decay (Luisi 2007).

An autopoietic unit or cell is understood as a dissipative and open system in constant exchange with its environment, which happens via a semi-permeable boundary, enabling specific inputs and outputs. The boundary itself is generated by the system, and undergoes constant renewal. In case of a living cell, specific nutrients are assimilated which serve as the means of energy generation, which, in turn, maintains the regeneration of the system from within (Luisi 2007).

This openness of an autopoietic unit entails a distinct interdependency of the system with its environment. Luisi (2007) suggests that this selective input can be understood as a basic characteristic of cognition.[9] In the case of a living cell this cognition expresses itself through the ability to determine the chemicals it extracts from its environment, which are consequently permitted to permeate the cell wall (Luisi 2007).

8 Criteria of autopoiesis, after Varela (2000)

1. Self-boundary: Does the system have a boundary of its own making?
2. Self-maintenance: Is the system capable of maintaining its own identity via dynamic processes, i.e. those components that are being used up are made anew by the system itself?
3. Self-generation: Does this happen throughout a network of reactions that are generated by the system itself?

9 The element of cognition as a common denominator of cellular life in combination with autopoiesis is disputed within the scientific community. Humberto Maturana, a leading scientist within the field of autopoiesis, believes, for example, that "Cognition is something that an observer says about a system, not a feature defining the system. Therefore, cognition is not a defining condition of a living system, dot a defining condition of life". (Maturana, in conversation with Luisi, (Luisi 2007, p.159)). The context of this research follows Luisi's model, locating the emergence of life in a holistic interplay between cognition, environment and autopoiesis.

For higher organisms, this cognitive ability is derived from the emergent interplay between different specialised cell types which, in their collective behaviour, allow for advanced cognitive characteristics such as advanced sensorial organs (Luisi 2007).

The reciprocal relationship between an autopoietic unit and its environment is particularly interesting, as they co-evolve and "design" each other through their constant exchange. As a dissipative system, such as an autopoietic unit, operates innately in a state out of equilibrium, it is inherently dynamic and permanently connected with its environment through an exchange of matter and energy.

Luisi (2007) concludes that "the compounds the living organism extracts from the environment can be seen as something that the organism itself lacks for implementing its life" and that "the appropriation of these missing parts is what gives 'meaning' and links the autopoietic unit with its world" (Luisi 2007, p.168). This relationship can be observed at the scale of a single cell, but is even more apparent when observing higher organisms, or even humans. A termite colony, one example Luisi (2007) presents, besides extracting nutrients from its environment actively transforms and shapes its habitat to sustain and advance the colony's propagation. In the case of humans this relationship has even resulted in the transformation of the natural environment on a global scale which meanwhile threatens existence of other species, including humans themselves.

The notion of autopoiesis as a concept has also permeated fields other than biology such as social science, in the form of social autopoiesis, and has even gained momentum in the architectural domain. Schumacher (2011), for example, suggests that the underlying principles and dynamics of the field of architecture – its design processes, discourse and history – can be understood as an autopoietic system. Schumacher's understanding of Autopoiesis is mainly concerned with the dynamic theoretical construct of architecture as a discipline and its evolution over time.

There is an ongoing discussion about whether life as such has to include biological cellular metabolism in physical space (Boden 1999). Boden (1999, p.242) states that "the concept of life is negotiable"; however, "since living matter cannot be created from nothing, growth and repair require that new molecules be synthesized by the organism – which molecules themselves make up the organism"(Boden 1999, p.237). Similarly, Maturana & Varela (1980, p.84) propose that "autopoiesis in the physical space [is] a necessary and sufficient condition for a system to be a living one".

This paragraph has offered a deliberately eclectic choice of inherently different concepts and abstractions, both chronologically and conceptually, of approximating biological self-organization and metabolism which ultimately constitutes biological life. The examples demonstrate the variety of layers of engagement, ranging from engineering and philosophy to architectural design.

The following project intends to contribute to this discourse with an demonstrator called Turm 2 (Tower 2) (Beyer 2015).

4.2. Demonstrator: Turm 2 (Tower 2)

The scenario approximates to an abstraction of biological metabolism through the demonstrator Turm 2[10] (Figure 33) and its ecology: an autonomous allopoietic construction principle based on the concept of material computation, which, in a speculative scenario, gradually transforms into a host for autopoietic sub-systems. The interface between environment and tectonics is here established through an active light-sensitive composite matrix which induces a local structural transition. The demonstrator operates within the previously outlined concept of transitional and reciprocal tectonics, which perceives the material transitions as well as the construction system as a feature of tectonic expression. The following paragraphs introduce the distinct elements of the scenario, and will conclude with an attempt to examine the project in relation to its metabolic characteristics.

4.2.1. Activated matrix through material computation

Material computation is understood as a physical form- (or structure-) finding process which utilises the ability of materials to respond to specific external conditions and changes. The notion of computation in this context is based on the specific information-processing capacity of materials (Menges 2012) – a specific input in the form of an external or internal stimulus which, through the intrinsic behaviour and characteristics of a material, translates into a distinct output which can, for example, can express itself in morphological changes (Oxman 2012; Menges & Schwinn 2012). This notion of a material as a computing entity has been used for design and architecture, and enables features such as responsive actuation.

The previously outlined projects (ICD/ITKE Pavilions) operate with the idea of material computation; however, the materials employed in the projects are only reacting to a set of intrinsic parameters. For example, the resin applied for the composite matrix cures independently from an external impetus after a certain time.

The HygroScope: Meteorosensitive Morphology project (Reichert et al. 2015), for example, utilises the hygroscopic properties of wood to actuate an opening mechanism. In this example, wood actively responds to an increase in humidity through the extension of its volume,

10 The project was shown as an artefact in the context of my architectural engineering diploma exhibition at the University of the Arts in Berlin 2015. The focus was on the mechanical principle of the winding process, sustainability aspects and site-specific application. A contextualisation in relation to the notion of allo/autopoiesis, material computation and biological metabolism was at this stage not attempted. Due to the project's involvement for the awarding of an academic degree it is not an objective to provide a full technical and material/structural assessment. However, for conceptual coherence and relevance to the development of Scenario 2 the main objective and project description will be provided.

Figure 33 Turm 2, Beyer 2015; final structure →

which is then translated into a functional feature. In this example, the material responds to a set of extrinsic parameters.

The following project utilises material computation in the domain of composite materials in two ways: firstly, through a physical form-finding process, dependent on yarn properties and their tension and friction. In this case the fibrous structure settles into a specific shape in accordance with the equilibrium of forces.

A secondary, time- and environmentally dependent reaction (extrinsic) takes place on a matrix level. Here, a UV-reactive resin responds to the environmental light intensity and initiates a gradual structural transformation. A further layer of dependency is created by the solar-powered winding process which similarly adapts to external light conditions.

4.2.2. Setup, technology and process

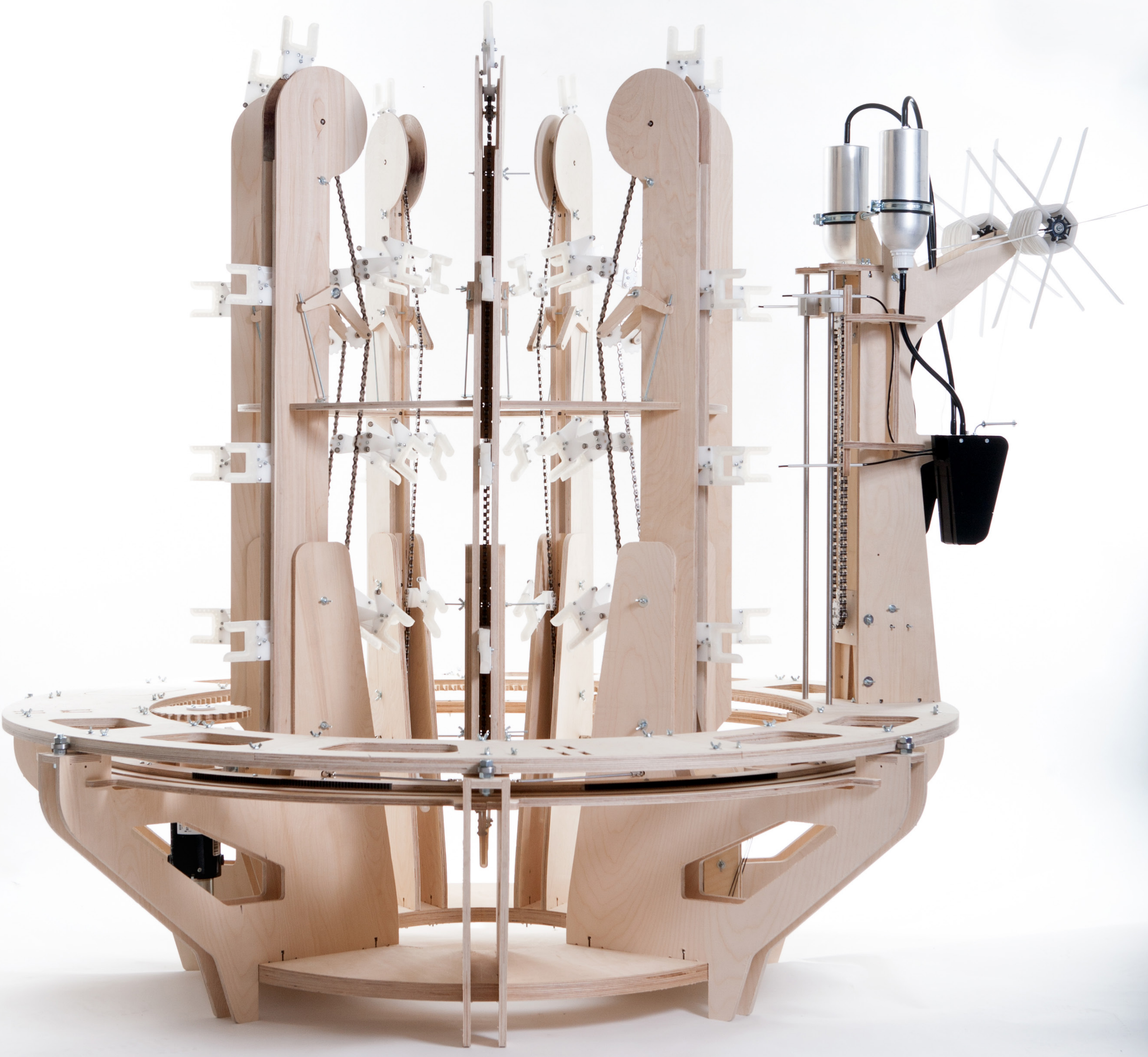
The following section will discuss the technical, functional and processual aspects of the project to illustrate the initially setup ontological framework. A further investigation into the relation to metabolism will be made in the discussion. The outlined 2014/15 and 2016/17 ICD/ITKE Pavilions, exhaustively displayed the morphological and structural potential of fibrous construction. However, their manufacturing relies heavily on energy-intensive and petrochemically dependent resources, in the form of carbon and glass fibres as well as synthetic resins.

The Turm 2 project (Figure 34) investigated a different pathway in relation to the materiality of fibrous construction, as well as the automation and fabrication of wound composites. The project aimed for an architectural system which was able to be used to autonomously erect a large-scale composite tower structure through an (almost) energy-neutral manufacturing process.

The materials employed during the manufacturing process were entirely bio-derived. Conventional cotton was used as a continuous fibrous reinforcement, while the matrix material comprised a linseed oil-based UV-curing and non-toxic bio-resin. The base (automaton) of the installation functioned as a manufacturing unit as well as a foundation for the tower.

Conceived in a heptagonal layout, seven vertical carriers with an array of nodal points in the form of silicon clamps served as winding nodes which constrained the fibres in one area, thus enabling a gradual bundling of fibres. Furthermore, the base incorporated a print-head with two spools of yarn and a resin tray in which the yarn was impregnated (Figure 36) while being applied to the individual nodes. Inspired by mechanical clockwork, a constant circular

Figure 34 Turm 2 automaton →



movement was translated into a choreography of three-dimensional winding patterns through interdependent mechanical means.

This approach enabled the automaton to rely solely on one electric motor, which reduced the need for complex electronic systems and control entities. Moreover, the system did not depend on the sophisticated computational tools which are needed for robotic assembly. During the fabrication process the print-head perpetually circled around the seven carriers equipped with the silicone nodes (Figure 37) in a horizontal movement (Figure 35). A secondary mechanical sub-system, dependent on the primary circular rotation, initiated a simultaneous vertical movement of the print-head. The combined choreography of both (horizontal and vertical) movements enabled diagonal pattern.

The uncured fibre layers continuously reiterated their state of equilibrium between the nodes, forming a distinct morphology mediated by the properties and behaviour of the material itself. The cured sections were gradually elevated by the moveable nodes while new material was successively added from the base. The control of the interval of elevations enabled a graded material deposition, which resulted in thicker segments at the lower part of the structure and thinner ones towards the top.

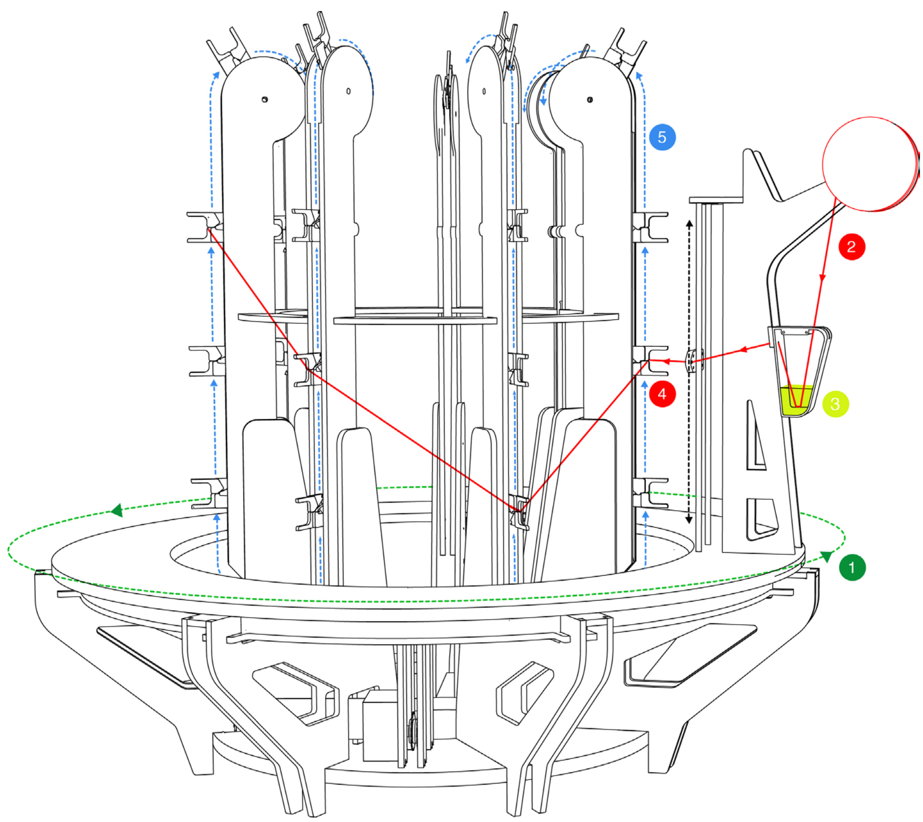


Figure 35 Turm 2 winding scheme

Figure 36 Details: fibrous base material spool and feeding mechanism, resin tanks

Figure 37 Nodal points, clamp system for vertical movement

Similarly to the ITKE/ICD projects presented previously, the Turm 2 project incorporates the idea of a coreless winding technique (Knippers & Koslowski 2017). However, the proposed technique enables the autonomous manufacturing of composite systems which exceed the dimensions of the scaffold they are generated with. This feature is enabled by the movable nodal points constantly pushing the structure upwards, while at the same time allowing new segments to emerge at the at the base. The technique could therefore be termed "continuous coreless winding".

Figure 38 illustrates the material and energy aspects of the Turm 2 concept. The raw materials were sourced from renewable crops, namely cotton (1) and linseed (2). Their development depends on photosynthesis (3) to deliver the resources for raw material extraction – in this case cotton and linseed oil. Semi-finished materials emerge from the refinement of the raw materials. A cotton yarn is spun (4) and the extracted linseed oil is processed to UV-active resin (5) which form the two constituents of the composite. In a further step, the manufacturing took place, as described above, using sunlight to power the installation (6).

Conventional resin-based composites have to be heat-cured in an energy-intensive process, which also has to be taken into account in relation to the environmental impact of composites. In the Turm 2 project, the curing is gradually established through the specific light conditions in the environment, therefore no external energy is needed for the curing process.

Due to the use of solely bio-derived materials, the finished structure is completely biodegradable and can, through natural decomposition, provide nutrients which future crops

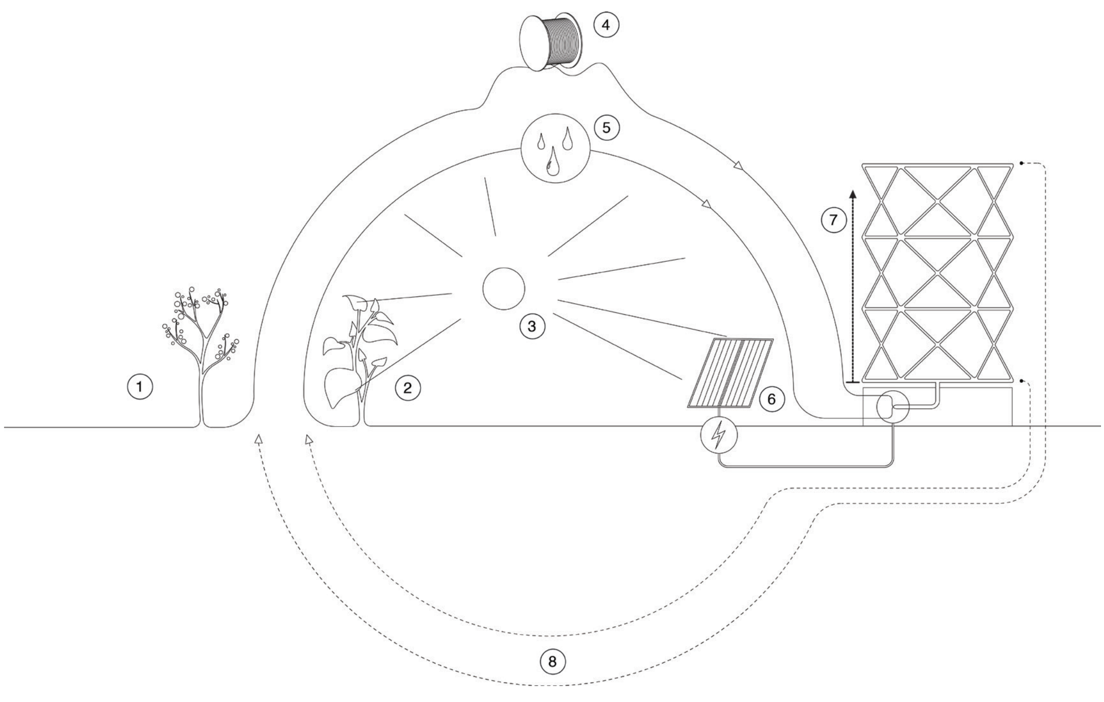


Figure 38 Energy and material concept

Figure 39 mechanical transmission of horizontal to vertical movement

Figure 40 Individual nodal "belts"; interior view

can harness (8). The system therefore presents an (almost) energy-neutral fabrication process, utilising sustainable fibre-based composites.[11] In contrast, conventional materials such as aluminium or plastics generate enormous amounts of CO2 during their processes of raw material extraction, refinement and production, as well as recycling (Benjamin 2017).

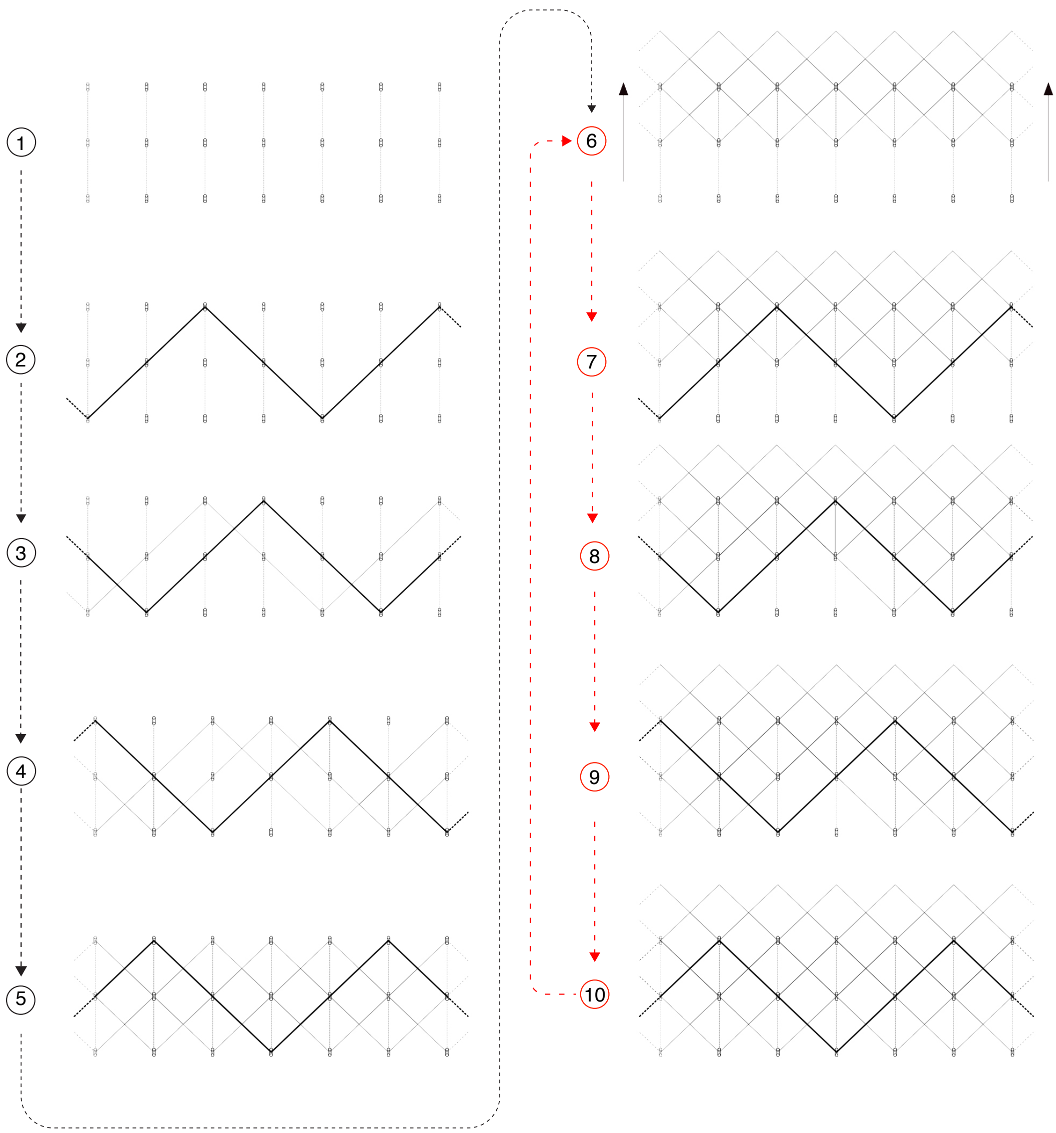


Figure 41 winding scheme

11 The cultivation, sourcing and refinement of the raw materials, as well as the materials the installation is made from, requires a certain amount of energy during their making. These secondary energy balances are, in this context, not taken into account, as they are, in the context of this conceptualisation, understood as “static”. While they are relevant for the overall energy and CO2 balance, they do not directly impact on the dynamic system illustrated in (Figure 38).

Figure 42 Clamp nodes, front

Figure 43 Clamp nodes, back

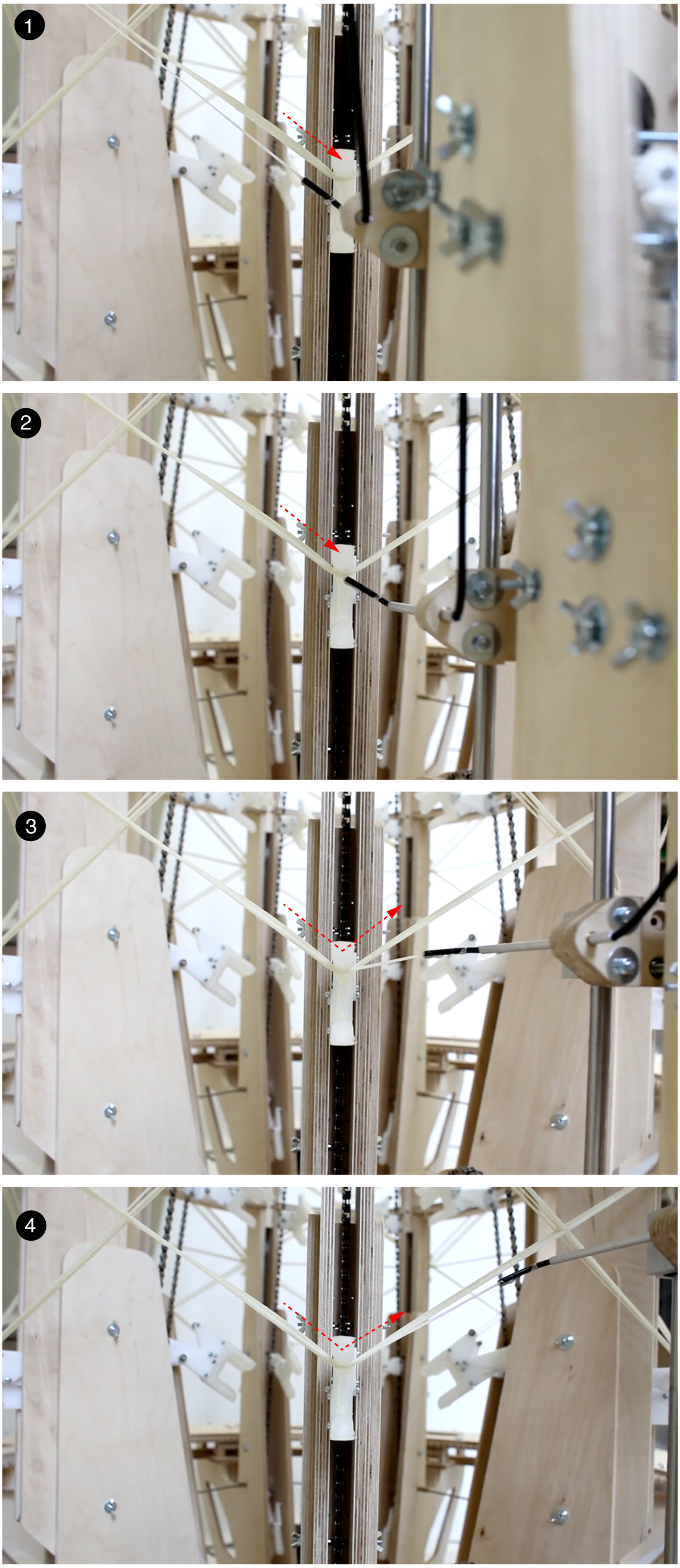


Figure 44 winding process

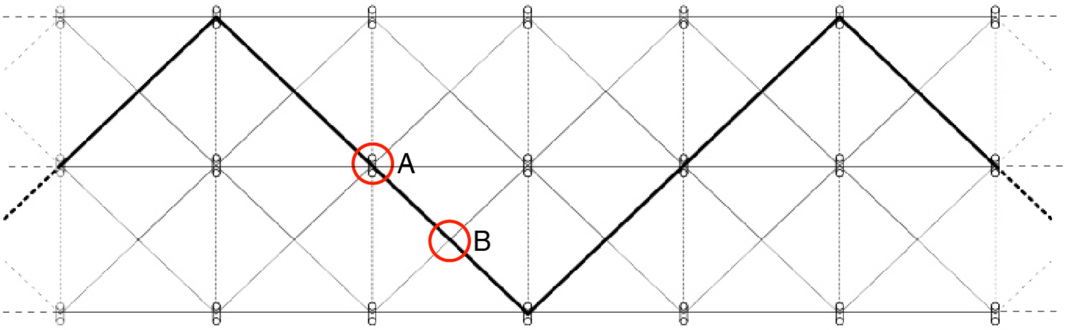


Figure 45 Clamp nodes, front

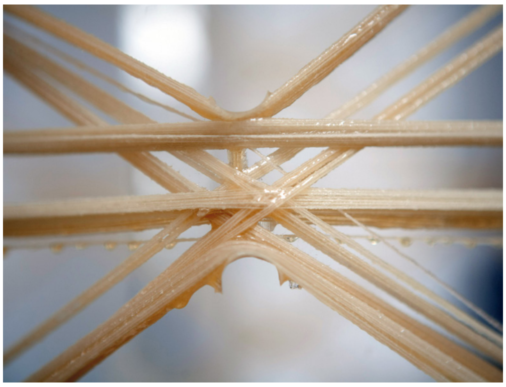


Figure 46 Detail area A

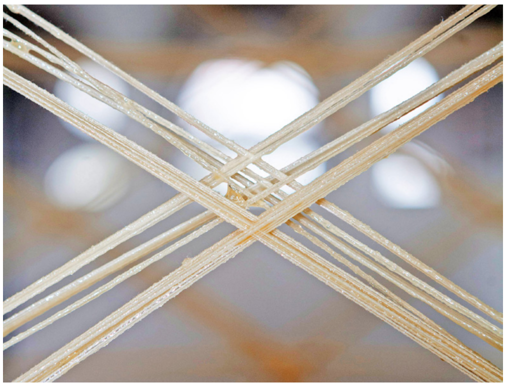


Figure 47 Detail area B

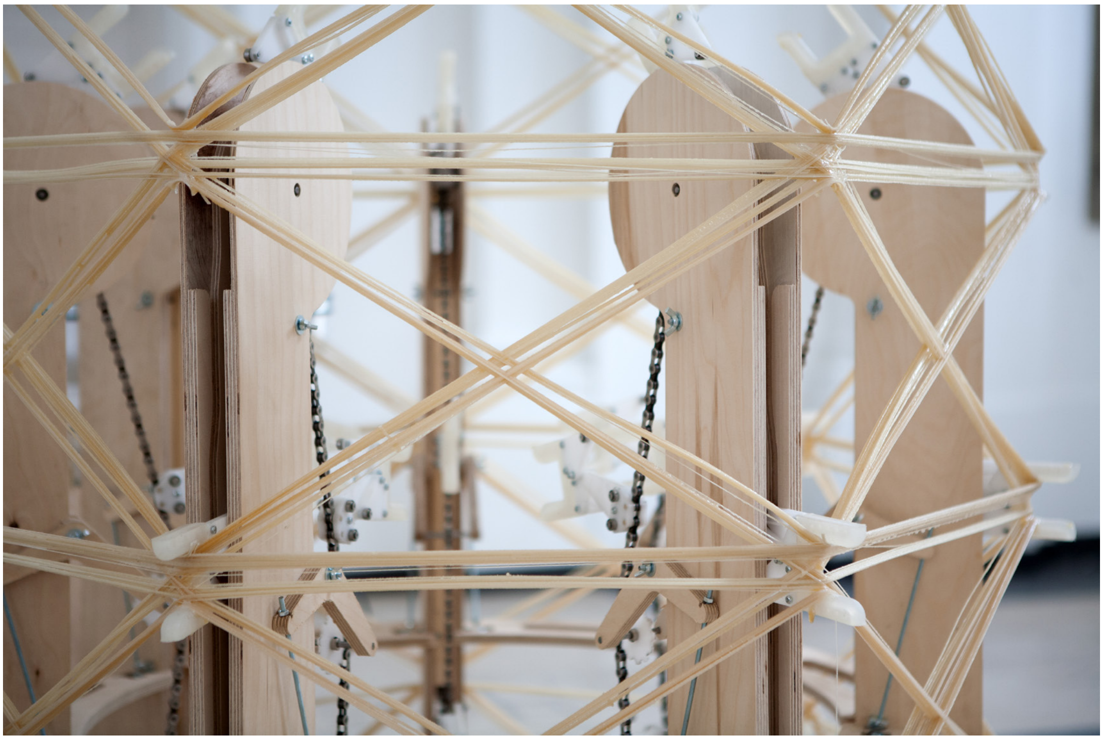


Figure 48 Automaton and composite structure

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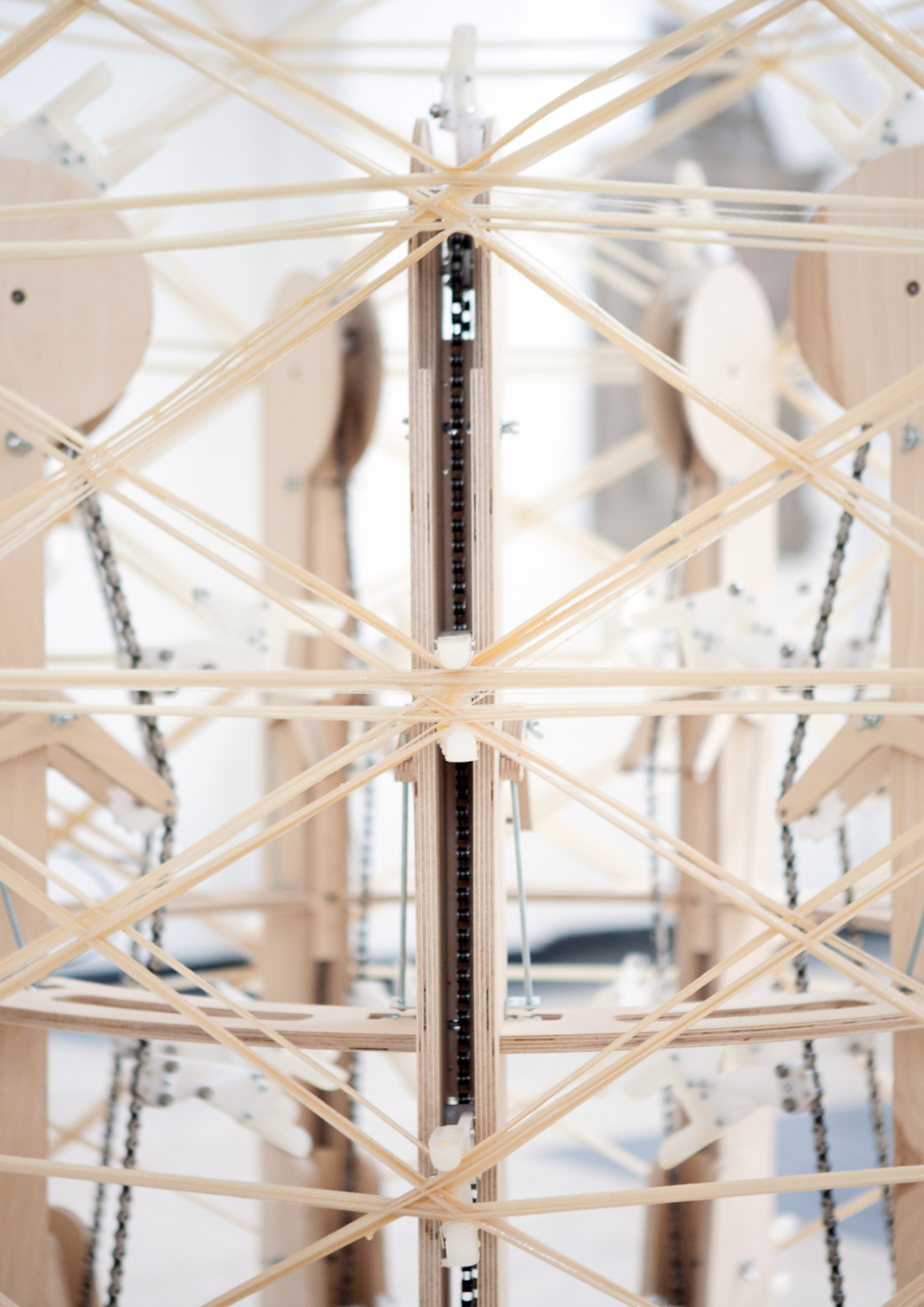
Figure 49 Installation UdK (2015)

Figure 50 Composite structure, nodes



4.2.3. Implication and ecology

The project was implicated in a speculative scenario for an application as a means for a remediation strategy of the Aral Sea Basin. The Aral sea lies between Uzbekistan and Kirgizstan, and is fed mainly fed by two rivers, Syr Darya and Amu Darya (Whish-Wilson 2002). Formerly covering approx. 66.000 km2, the Aral Sea used to be the fourth largest lake in the world and the biggest in Asia. The flourishing cotton industry has influenced the natural hydrology through the redirection of the inflows which feed the Aral Sea, hence heavily contributing to its gradual desiccation (Figure 51). Since the 1950s, extensive irrigation projects for cotton plantations caused a decrease in the lake's water volume of around 80% (Whish-Wilson 2002). The fall of the water level by approx. 19m exposed 3.6 million hectares of seabed. Through evaporation and the lack of inflow water the lake's salinity increased, leading to the extinction of the prevailing aquatic life. Furthermore, the water contained increased amounts of fertilizers, as well as large quantities of pesticides. The repercussions of the desiccation process produced a salt-encrusted, heavily contaminated and exposed seabed (Whish-Wilson 2002). Strong winds have successively eroded the toxic residues and spread them throughout populated areas,

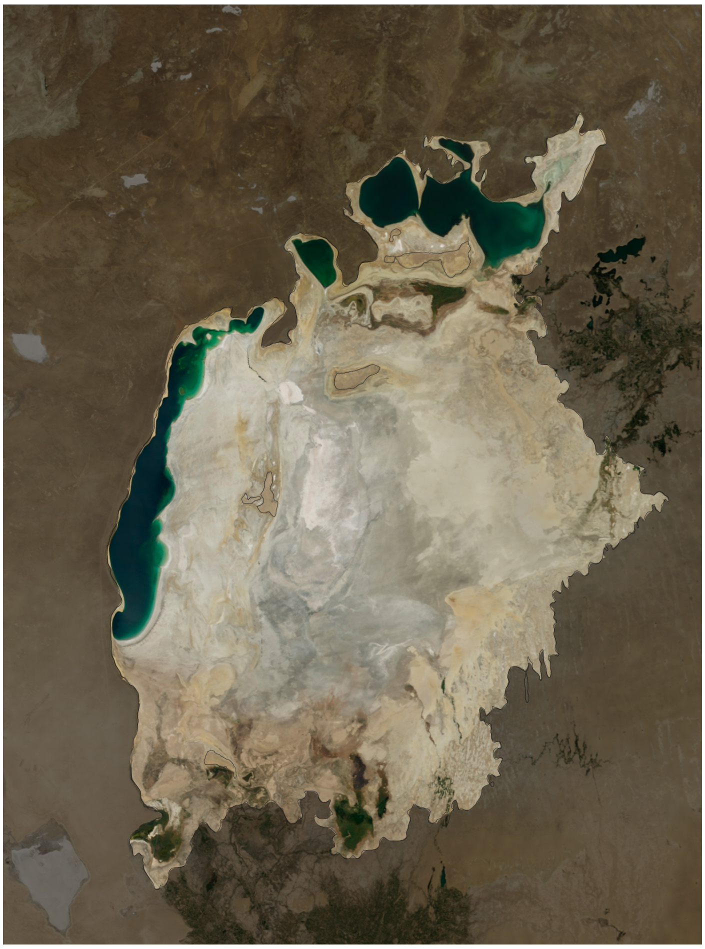


Figure 51 Aral sea before and after desiccation

leading to increased health problems related to this effect. The speculative implication of the Turm 2 project aimed at employing local resources such as cotton waste-products and linseed oil to autonomously erect towers within the hostile environment. The towers were designed to incorporate dew-collecting textile elements, which would feed an integrated reservoir (Figure 57). Successively, the reservoir would release water to its immediate environment to initiate the start of a new vegetation with specific pioneering organisms in the form of plants which can cope with the prevailing levels of salination and toxicity.

After gradually introducing the pioneer colony, a more diverse ecosystem can gradually form and contribute to an improvement by counteracting the ecological impact of the desiccation.

The vegetation would help to successively bio-degrade the toxins and dilute the salt content of the seabed while solidifying the ground through root networks, reducing the erosive processes. Furthermore, the tower arrays would act as windbreakers to slow down the heavy winds in the ground area (Figure 52).

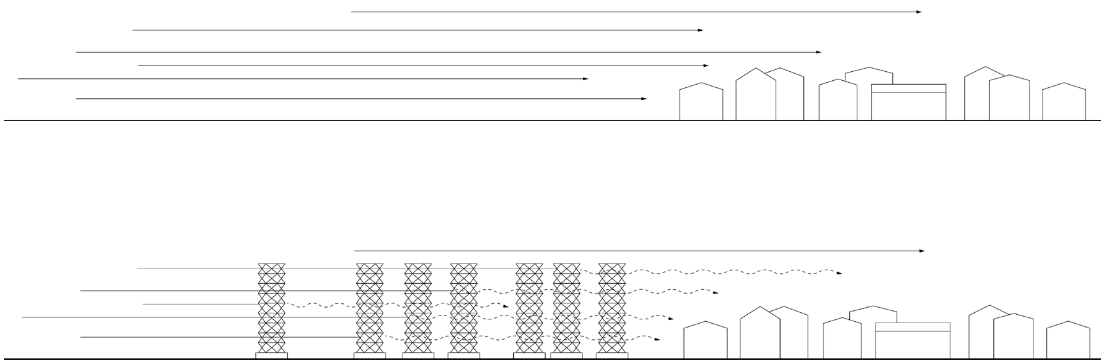


Figure 52 Wind barrier concept

Figure 53 Aralsk site plan

Figure 54 Aralsk potential area of intervention

Figure 55 Automated structure generation; step 2 unfolding solar panels; step 3 onwards composite winding

Figure 56 Front and top view

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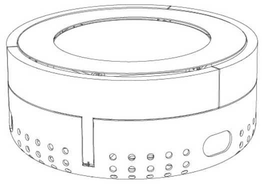
1



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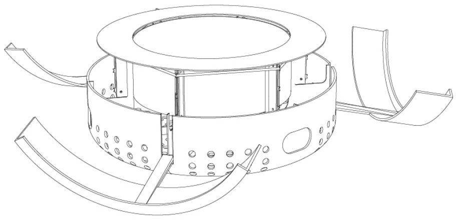

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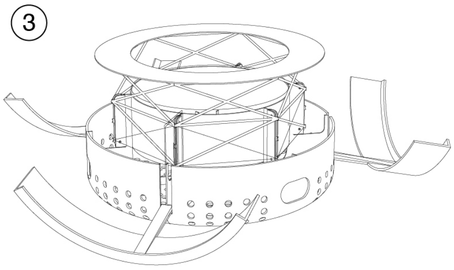

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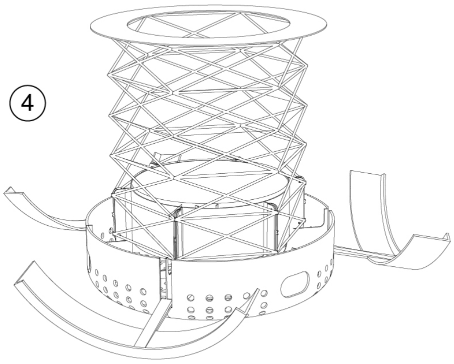

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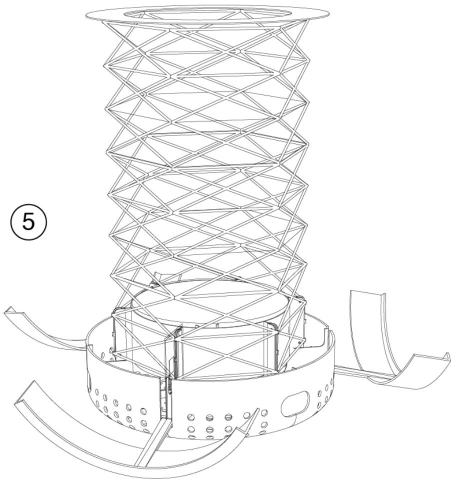

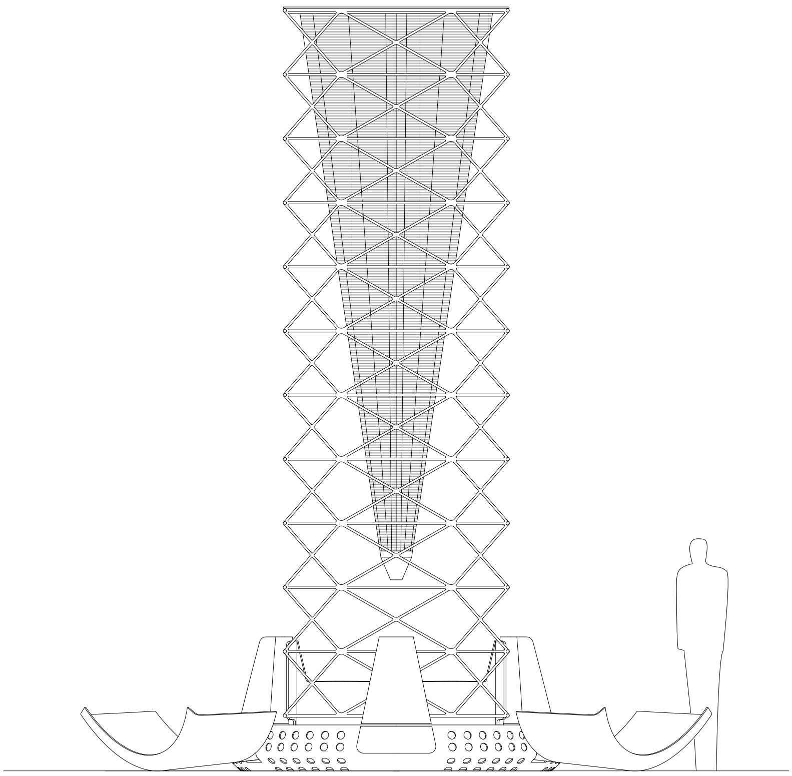

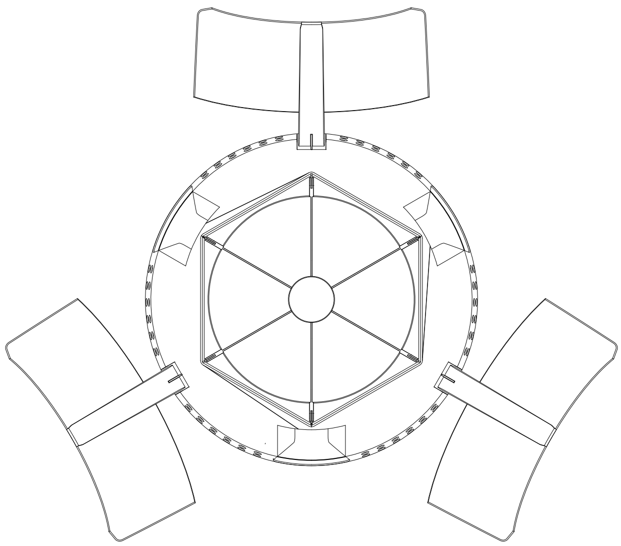

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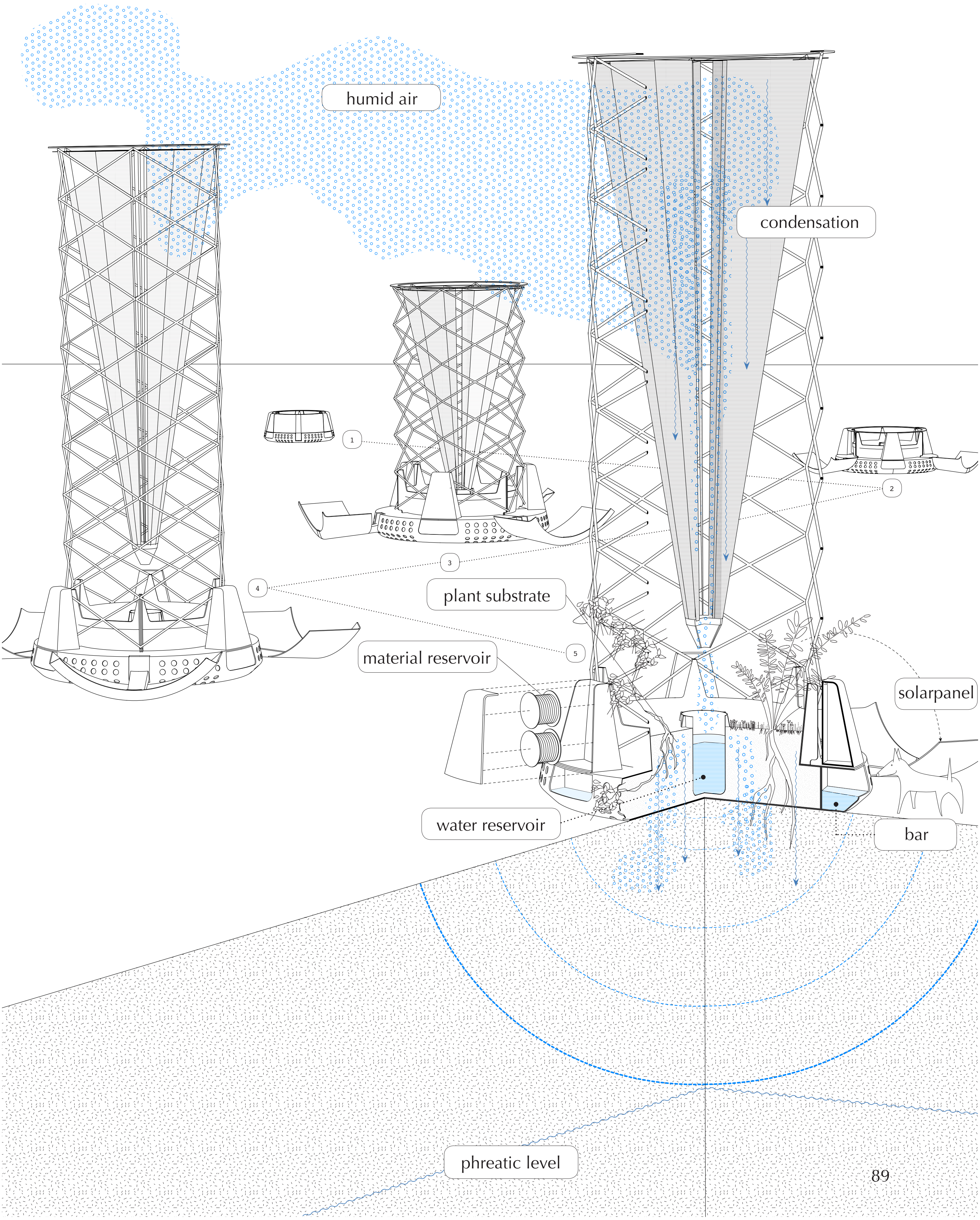
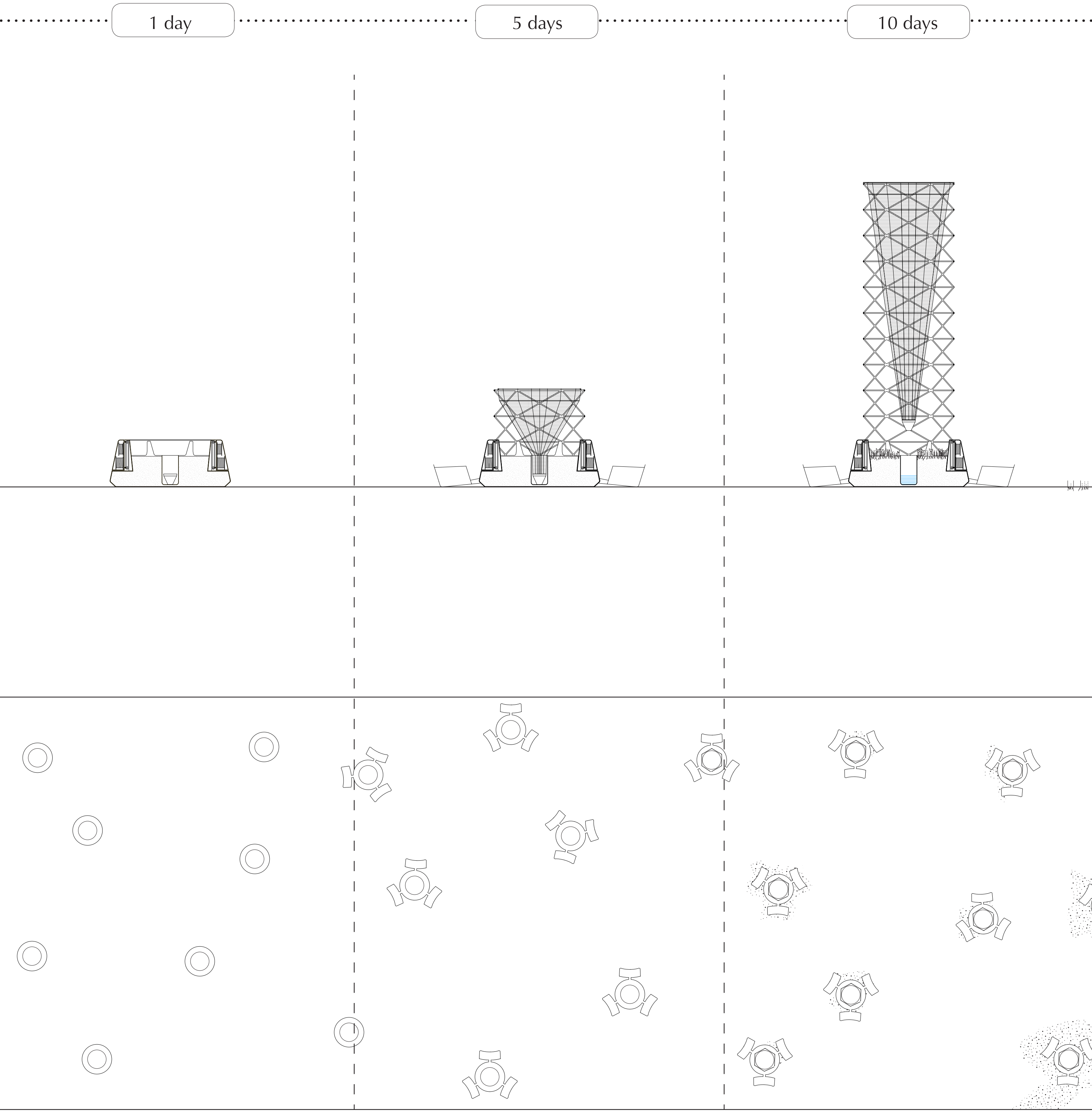
Figure 57 Intervention scenario

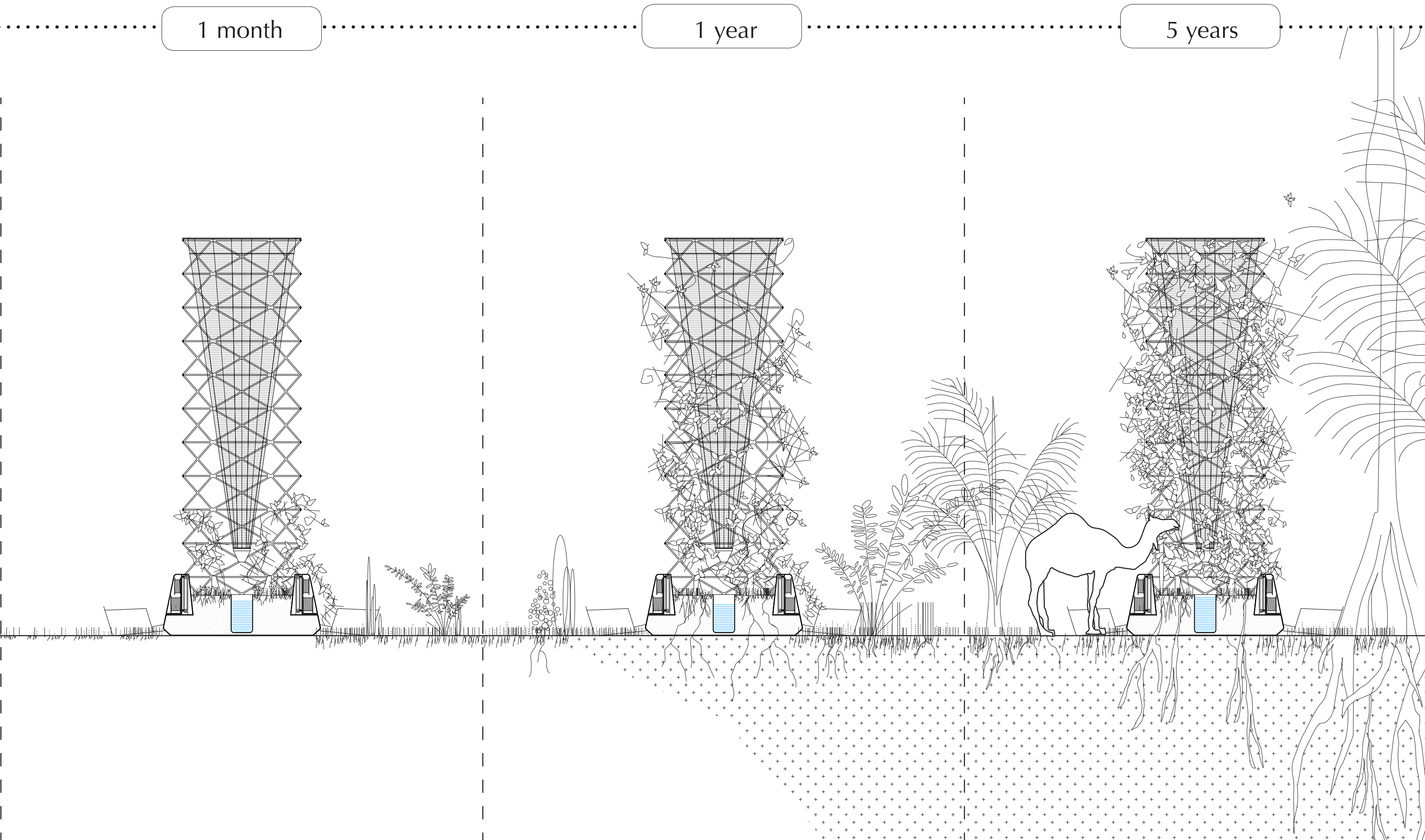
Figure 58 Speculative scenario timeline

Figure 59 Sepeculative scenario rendering 1

Figure 60 epeculative scenario rendering 2


humid air
condensation
1
2
3
4
5
plant substrate
material reservoir
solarpanel
water reservoir
bar
phreatic level


1 day
5 days
10 days


1 month
1 year
5 years

4.3. Discussion

Metabolistic analogy

Minimal external energy is required to power the main winding mechanism of the automaton, which can potentially be provided by solar panels. In such a configuration, the manufacturing of the structure is directly linked to the natural light cycle to power the machine and at the same time initiate the curing process through the UV-spectrum of natural light. This dependency also elevates the generated material from being merely a passive construction medium. The material actively reacts to the environmental conditions on site while embedding this information in the material during the process of its generation, similar to growth rings of natural wood (Figure 46, Figure 47).

The scenario demonstrates an analogy with biological metabolism, displaying both anabolic and catabolic characteristics. The process of biological metabolism "refers to the use, and budgeting, of energy for bodily construction and maintenance, as well as for behaviour." (Boden 1999, p.236). As outlined previously, two main metabolic processes can be distinguished – anabolic and catabolic metabolism – which relate to the utilisation of energy and matter (Voet et al. 2013). Catabolic processes relate to the breakdown of compounds to obtain energy, while anabolic processes synthesise compounds needed for maintenance and construction (repair, self-replication).

In the scenario presented, the demonstrator harnesses energy in form of sunlight, which powers the main winding principle. Simultaneously, this energy contributes to the formation of structure through light-dependent material transformation. The translation of sunlight into (chemical) energy, also found in nature, which drives the growth process, is understood as photosynthesis. It is a special form of anabolic metabolism and is ubiquitous in the plant kingdom.

Boden (1999, p. 235) outlines that "metabolism is the use of energy-budgeting for autonomous bodily construction and self-maintenance" (Boden 2000, p.122) where "each living system has assigned to it, or collects for itself, a finite amount of energy. This is used up as it engages in its various activities". Boden (1999) stresses the notion of *itself* as a distinct feature of metabolic systems. The scenario outlined envisions a principle which can autonomously utilise the energy provided from the environment for the construction and the material transformation. Boden (1999, p 235) continues by saying that "when the individual's energy is spent, either because it is no longer available in the environment or because the system can no longer collect or use it, the energy-dependent behaviour must cease and the creature dies." However, "bodily maintenance is normally continuous, (…) the underlying metabolic processes are more active at some times – of the day, year, and life-cycle – than at others. Sometimes, they are drastically slowed down, or (perhaps) even temporarily suspended" (p.238). Metabolic activity in organisms can therefore vary in case of events such as hibernation or freezing, depending on the available energy. Another analogy can be drawn here as the demonstrator adapts its generation of structure in relation to the energy it can obtain from its environment, which is directly translated into structure. Living organisms developed strategies for storing the extracted energy for a certain amount of time, making them more independent from their immediate environment; however, Boden (1999) suggests that "simplest conceivable living thing(s) might take their energy directly from the environment whenever they needed it." (p.237).

The purpose of this attempt is not to claim the attribute "alive" for the demonstrator, but to outline the parallels which can be drawn with biological metabolism. The demonstrator, in the way it works, still resembles an allopoietic construction principle which contrasts starkly with autopoiesis[12] (a further approach can be found in appendix E). The demonstrator is not self-reproducing, but displays some characteristics of biological systems. It could be demonstrated that the system is able to act autonomously in a distinct environment and respond to it with (non-biochemical) catabolic and anabolic reactions, which utilise natural light as an environmental source of energy, which is in turn translated into a structure. Furthermore, it suggests a material cycle (Figure 38), including the decay and regeneration of the system through a natural metabolic cycle.

This conceptual layer incorporates a complete material cycle; however, it implies leaving the demonstrator as the focal point, and adapting a more fragmented abstraction of the metabolistic principle. It also relies on other actors such as humans and machinery for activities such as harvesting and raw material production. This notion of a higher-order metabolism departs from the direct biological analogy and aligns more with the metaphoric interpretation of the Metabolist movement in architecture.

However, the Vaucansonian duck, described earlier, proposes, in a similar mechanical manner, an analogy to a metabolic system, but the approaches are formulated inherently differently.

12 Whereas autopoiesis generates "itself" through its inherent processes, allopoiesis produces "something different from themselves" (Buchinger 2006, p.362). This concept applies to most processes of human production, and similarly to the concept of reproduction in biology. However, while the result of biological reproduction does not constitute "itself", the underlying principle is driven by autopoietic workings on a cellular level. This illustrates that autopoiesis or allopoiesis are not to be seen as absolute systems: it is more that they vary with the observer's perspective.

On a formal level, the duck imitates precisely the physiognomy, including the intestines[13], of its living paragon. These features do not, however, move on from the formal level – although it can dissolve the food through a chemical process, the duck cannot draw its energy from this source. Furthermore, an external input of kinetic energy is needed to power the system, so it is not self-sustaining.

The presented demonstrator departs from a literal copying of any organism in its physiological constitution. Similarly, the "digestion" is translated into a different energy and material domain. Like a plant, the scenario utilises sun to power and transform its structure. Analogous to the duck, the demonstrator "eats" and "digests" sun, which powers a composite winding process, resulting in a UV-responding structure.

13 Wood (2002) quotes Vaucanson, outlining functions of the digestive tract where food was "driven away at Pleasure through circumvolutions of pipes" and passed to "bowels, then to the anus, where there is a sphincter which permits it to emerge."

5. Biology II: The textile microbiome

The previous chapter presented biology, specifically biological metabolism, as a highly successful model from which to draw formal, systemic and functional analogies.

Millions of years of evolution have shaped these processes and organisms, including the human body, dexterity and intelligence. In an almost self-reflective process we deduce knowledge from our own creation to inform our creations.

Another approach is to work directly *with* biology in order to create materials, thus harnessing the direct performance of biological metabolism. This strategy has been applied over centuries in the context of food production. We ferment foods, inoculate cheese with fungi or brew beer with yeast to enhance their preservability and taste (El-Mansi & Bryce 2007).

This approach has also most recently permeated the domain of design and architecture, in which microorganisms are harnessed for their distinctive adaptiveness/responsiveness, their sustainability and their ability to generate structures (Travaglini et al. 2013; Benjamin 2017; Cruz & Beckett 2016; Myers 2012; Hebel & Heisel 2017). The following chapter will investigate the potential contribution of this approach for the domain of tectonic composites and introduce the concept of the active textile microbiome and metabolising matrices.[14]

5.1. Bioderived-Matrices

The recent advances in the development of bio-derived polymers and thermoplastics promise a more sustainable approach to polymer-bound composites (Netravali & Pastore 2014). These materials are designed as a substitute for conventional petrochemically derived polymers by mimicking their behaviour. Although these materials deliver a technically very advanced and sustainable alternative to synthetic materials, they are usually functionally as well as morphologically indistinguishable from their synthetic siblings (Netravali & Pastore 2014). Bio-derived polymers usually utilise plant by-products such as oil, protein or carbohydrates (mainly starch and cellulose), which are modified through specific chemical processing forming polymeric substances (Wool & Sun 2005).

14 A perspective on modern biotechnology including synthetic biology is provided in appendix F. As the project is not engaging with the organisms on a DNA level or utilizing GMO organisms an in depth introduction is at this stage not necessary, however considered relevant for further implications of the concept.

Mycelium hyphae microstructure

http://www.musarama.org/upload/high/fusarium-mycelium.jpg

(Image redacted for copyright reasons)

Figure 61 Mycelium microstructure magnification; Chitin Hyphae

Mycelium structure within substrate

https://insteading.com/blog/mycelium/

(Image redacted for copyright reasons)

Figure 62 Mycelium macrostructure

A different strategy is offered by harnessing natural growth itself to generate matrix material within a suitable substrate. This approach utilises the properties of specific microorganisms to actively form materials such as nano-cellulose or chitin fibres in the form of mycelium (Myers 2012). In contrast to the use of plant-based by-products, which includes the initial cultivation as well as the processing of a suitable plant, this strategy utilises the natural behaviour of specific microorganisms to form a material. The process, therefore, renders the intermediate steps of material processing obsolete.

In this context, a differentiation has to be made between either secondary bio-derived matrix materials, which have to be processed to be applied (such as bio-resins), and primary bio-derived matrix materials, which are able to form materials and structures through their intrinsic natural behaviour.

Specific primary bio-derived materials such as mycelium, the root material of fungi, display interesting properties such as insulative characteristics while achieving strength ratios similar to foamed polystyrene. The specific characteristics enable the use of the material for construction purposes (Travaglini et al. 2013).

The fungal organism can be cultivated on various bases, such as agricultural by-products or wood-based waste material, which makes it versatile and independent of raw material, and thus a cost-efficient material system. Projects like David Benjamin's MoMA PS1 Pavilion (2014) (Figure 64) or the MycoTree project by the Block Research Group, which to a large degree consists of bricks made from mycelium-bound materials (Figure 63), demonstrate its application within the architectural domain. The individual bricks are manufactured through controlled cultivation of mycelium in a medium comprised of agricultural by-products.

Nanocellulose generated by bacteria is another sample of a versatile biomaterial which has been considered as a potential matrix material. The material is biocompatible, and has translucent characteristics (Lee et al. 2014). Because its properties are similar to natural leather, some designers have used it in the context of fashion and shoe design. (Hemmings 2008) (Figure 66). Some strains of bacteria are able to trigger biochemical reactions, such as calcifying the medium they are inhabiting, forming a concrete-like material which can be utilised for building purposes (Esnault Filet et al. 2012).

These examples, which will be investigated in more detail at a later stage, illustrate the wide range of different materials which can be generated by living organisms and can potentially be utilised for novel fibre-based composite materials.

Mycelium and wood substrate

https://www.mogu.bio/

(Image redacted for copyright reasons)

Figure 63 Wood chips embedded in a mycelium matrix

Hy-Fi tower, MoMA PS1

http://www.thelivingnewyork.com/

(Image redacted for copyright reasons)

Figure 64 David Benjamin, Hy-Fi tower, MoMA PS1 Pavilion, 2014 © the living NY

Not only are these microorganisms able to generate complex materials, but also, due to their active role in the material system, they are potentially capable of enabling material features such as adaptivity and reactivity, as well as self-healing (Cruz & Beckett 2016; Jonkers & Schlangen 2007; Lee, Shamsuddin, et al. 2014). The manufacturing process of primary bio-derived materials is inherently different from conventional production methods. Depending on the microorganism's specific needs a distinct setup has to be considered, which sometimes consists of a sterile working environment or an incubation process in a monitored environment over several days or weeks. These procedures are rather unusual in the context architectural materials, although they also offer new potential for the design process.

The three examples of biological processes (mycelium growth, bacterial cellulose and bacterially induced calcite precipitation) mentioned above have been explored in the field of design and architecture; however, there has been little research into how these materials behave on fibre-based materials. As discussed in the previous chapter, the development of composite materials depends on three main fields of science, namely fibre development, matrix-materials and automation technology. In addition to these this research project seeks to introduce the field of biotechnology: to foster the potential and advances of modern biotechnology for the development of novel bio-fabricated composites.

Biotechnology and architecture seem to be diametrically opposed disciplines at first glance, albeit we share our spaces and buildings with myriad of other microbiological inhabitants which form a whole microcosm beyond our (direct) perception. The study of the built environment microbiome is concerned with their taxonomy and relationship with humans hence generating a disciplinary overlap between applied microbiology and architecture. The following chapter comprehensively introduces this field while outlining its relevance for this research.

Bacteria and cellulose fibres microscopy

Guided Growth - Design and Computation of Biologically Active Materials (Zolotovsky, 2017) p.63

(Image redacted for copyright reasons)

Figure 65 cellulose generating bacteria

Bio Couture, garments

https://www.naturalblaze.com/2016/04/the-woman-who-grows-her-own-kombucha-clothes.html

(Image redacted for copyright reasons)

Figure 66 Suzanne Lee's "Bio Couture" bacterial cellulose as a leather substitute

5.2. The built environment microbiome

Humankind shares the natural, as well as the built, environment with a vast range of different microorganisms and, often unknowingly and sometimes involuntarily, forms complex relationships with them. Trillions of microorganisms, including non-pathogenic commensal organisms, that benefit from the human (environment) without causing harm, as well as human pathogens, colonise the architectural environment (Kembel et al. 2012). These organisms comprehensively inhabit every part of the built environment, ranging from ventilation systems to surfaces and architectural utility infrastructure (Adams et al. 2015). The range of microorganisms which humans share their spaces with form the built environment microbiome (Kembel et al. 2012). Burge (1988) states that a microbiome

> may be defined as a characteristic microbial community occupying a reasonably well-defined habitat which has distinct physio-chemical properties. The term thus not only refers to the microorganisms involved but also encompasses their theatre of activity (ibid.,1988: p176)

The human body itself is host to a vast range of organisms inhabiting different parts of the body: this is known as the human microbiome, and comprises several sub-biomes. For example, the human skin and gut are occupied by various organisms forming, respectively, the human skin microbiome (Grice & Segre 2013) and the human gut microbiome (Yatsunenko et al. 2012). These different microbiomes comprise different communities of microorganisms which have adapted to their specific habitat. However, the various microbiomes surrounding and inhabiting the human body are also in constant exchange with each other. The skin, as the human body's largest organ, can also be understood as the interface which stands in direct and constant relationship with the built environment microbiome (Lax et al. 2016). Research suggests that there is a direct correlation between the microorganisms humans are exposed to in their built environment and their physical, and even mental, health (Stamper et al. 2016).

With our growing understanding of the significant role of the human gut microbiome for human health and psychology (Cryan & O'Mahony 2011) the notion of the reciprocal correlation between the built environment microbiome and the human microbiome becomes increasingly important for a holistic design approach for architecture which fosters the wellbeing of its inhabitants. Modern biotechnology not only enables the sampling and categorising of individual microorganisms or microbiomes, but also offers the opportunity to actively design and control them.

Cruz and Beckett (2016), for example, explore the concept of a designed active microbiome in the context of architecture with façade panels which incorporate living organisms. The experiment deploys selected cryptogams which would, once the material is inoculated, propagate and gradually colonise the panels. Their notion of *bioreceptive design* (Cruz & Beckett 2016) aims to foster biological activity for architectural design in order to generate interfaces which stand in constant biological exchange with their environment. The specific biomes thus influence the morphology of the building components, as well as utilising the biological activity to establish an environmentally beneficial relationship with the environment as well as the inhabitants.

In the context of textile-based composite materials, the design and distinct agency of a microbiome on a fibre level could similarly contribute to novel bio-receptive materials.

5.3. The textile microbiome

This research project investigates the concept of an *active textile microbiome* for the development of novel metabolising matrices. The notion of a textile microbiome has been established in the field of textile research and development. This concept suggests that, depending on the specific property of a fibrous material, as well as the environmental conditions it is used in, different types of bacteria are likely to colonise the textile material (Callewaert et al. 2014; McQueen et al. 2007). The main focus of the research on textile microbiomes centres around the specific bacteria strains which contribute to the development of malodour (e.g. in sportswear). This specific textile microbiome is established through interaction with the human microbiome. While wearing garments, the human body transfers parts of its individual microbiome onto the textiles which can, under certain circumstances, stay active and generate unwanted by-products which cause malodour (Callewaert et al. 2014). Certain microorganisms of the human biome display sufficient resilience to adapt and survive in entirely different conditions, such as fibrous materials. At the same time, a differentiation between the acceptance of different fibre types and distinct strains of bacteria can be observed, indicating that material, as well as the micro structure, play an important role in colonisation process.

The ability of natural fibres to absorb and maintain moisture, as well as their cellulose content, which can be utilised as a nutrient source by many microorganisms, can contribute to the development of a specific textile microbiome (Callewaert et al. 2014). However, most of the research in the field of textile microbiomes mainly concerns the undesired volatile by-products of specific bacteria strains in the context of the clothing industry. As textiles are currently undergoing a renaissance in the field of architecture and construction, due to material and fabrication innovations (Reichert et al. 2014; Thomsen et al. 2015), the notion of an architectural textile microbiome and its effect on architectural design should similarly be considered.

Every textile, whether worn on the body or used in an architectural context, develops a distinct microbiome due to its exposure and interaction with other biomes. These textile microbiomes, on either natural fibres or synthetic fibre products, are usually undesired as they can cause either the generation of volatile by-products which may contribute to malodour (McQueen et al. 2007) or hygiene and pathogenic problems (Figure 67 Figure 68), or even initiate processes of decay which result in a weakening of the materials (Shah et al. 2008). Therefore, the main research in the field of textile microbiomes deals with strategies relating to how to inhibit or quantify biological activity on textile media (Callewaert et al. 2014).

However, besides causing malodour, various microorganisms are, as outlined earlier, able to generate strong microstructures, which in turn can contribute to an active strengthening through the formation of bio-derived microstructures in the medium they are cultivated in.

The research suggests that the ability of textiles to foster the development of a biome could potentially also be used to design a beneficial microbiome on a textile medium which could actively contribute to the generation of a class of sui generis bio-active composite materials. The initial drawback, that textiles serve as a microbiologically active material, could in this context be utilised and therefore turned into an advantage.

Such a design process demands a taxonomy of specific strains of microorganisms which, instead of causing decay or unwanted by-products, add new features for textile materials by harnessing their intrinsic biological processes.[15] The resulting fibrous material would thus serve as a platform or scaffold for the biological activity: its biocompatibility towards the microorganisms is thus crucial for this material system. A material system composed of a textile material and a living organism would profit from the versatility of textile materials, as well as the distinct biological reactivity and active behaviour of a designed microbiome.

15 A biotechnical fabrication and design scenario for semi-finished fibre materials with a distinct microbiome is outlined in Appendix G

SEM microscopy, bacteria on fibres

https://www.micronaut.ch/

(Image redacted for copyright reasons)

Figure 67 Malodour-causing Staphylococcus saprophyticus bacteria on a fibrous substrate

SEM microscopy, bacteria on fibres

https://www.pinterest.nz/pin/386535580489411409/?lp=true

(Image redacted for copyright reasons)

Figure 68 MRSA bacteria on the fibres of a wound dressing

5.4. Microbiome-based material systems

A common attribute every microbiome shares is the colonisation of a distinct substrate. Unless the microorganism colonises another living organism (e.g. human skin), it generally consists of an active part, the microorganism which accounts for the biological (re)activity, and a passive part, the substrate. Therefore it can be understood as a material system or composite comprised of a substrate and a microbiome. The substrate in this context plays a significant role, as it needs specific features to provide a suitable habitat for the organisms to strive. Different organisms display different needs depending on their natural habitat; however, many organisms display a high resilience. Cyanobacteria, for example, can be found in almost every habitat on earth, from maritime hot springs to arctic environments (Whitton 2012).

In most cases an increased moisture content, a moderate temperature and a stable pH level contribute to the development of microbiological activity; therefore the substrate can be specifically designed to fit the needs of a particular organism.

Biological scaffolds, in the medical field of tissue engineering, are a contemporary example where this specific relationship between a passive substratum and an active cell culture is investigated and applied. This field encompasses a highly multidisciplinary approach, "drawing on experts from clinical medicine, mechanical engineering, materials science, genetics, and related disciplines from both engineering and the life sciences" (O'Brien 2011). The approach is concerned with the topic of using porous scaffolds to "provide the appropriate environment for the regeneration of tissues and organs"(Ibid, 2011). Important parameters for the determination of appropriate structures and scaffolds are biocompatibility, biodegradability, mechanical properties, scaffold architecture and manufacturing technologies (Ibid, 2011). The field mainly concerns human or mammalian cells for tissue engineering and implantation purposes, but these advancements may as well be translated to other cell cultures, different scales and environments.

Cruz & Beckett (2016), for example, drew on the biomedical understanding of scaffolds to coin the notion of bioreceptivity in the context of architecture. A bioreceptive material "has to be biocompatible with particular types of species that will colonise it in a specific environment"(Cruz & Beckett 2016, p.54).

The Biota lab at UCL, London, approaches the concept of bioreceptivity through applying methods from the domains of material engineering, as well as computational design. In the Computational Seeding of Bioreceptive Materials research project (Figure 69), an engineered Portland cement mixture provided an optimised pH level, as well as morphological features such as porosity and roughness (Figure 70). Cruz & Beckett (2016) argue that "the degree of

Bioreceptive wall panels

http://www.richard-beckett.com/bioreceptive-facade-panels.html

(Image redacted for copyright reasons)

Figure 69 "Computational Seeding of Bioreceptive Materials", BiotA lab (2016)

Bioreceptive material detail with cryptogams

https://www.instagram.com/p/BgJdQY8HikV/

(Image redacted for copyright reasons)

Figure 70 Detail colonised bioreceptive cement (BiotA Lab, M. Cruz) colonisation on surfaces is dependent on both the inherent properties of the material itself and environmental conditions; this area of work asks design to explore the relationship between the material substratum and areas of the surface that enhance or inhibit growth, as well as the specific environment and organisms that thrive in it", while the processes "involving designing with living organisms, will never be a static condition" (p.53).

Computational form-finding methods were applied to optimise the surface geometry of the panels. A functional morphology consists of flat areas collecting water which lead through grooves to indentations where moisture is collected and retained to promote the growth of cryptogams (algae, lichens, fungi, mosses) (Cruz & Beckett 2016). Thus a gradual proliferation takes place on the surface, creating a biologically active interface which can contribute to a reduction in pollutants and influence the climate surrounding its immediate environment.

The utilisation of a microbiome, however, can vary. While the microbiome in the project Cruz and Beckett conducted does not structurally influence its medium, projects such as David Benjamin's MoMA PS1 Pavilion project or Philippe Block's MycoTree project employ an active fungi biome to generate a substructure within a granular substrate (Figure 71). Mycelium, the root substance of fungi, gradually permeates the substrate while establishing a substructure, resulting in a gradual stiffening (Figure 72).

In order to be deployable for structural applications, the material has to be dried once the organism has permeated the structure, thus losing its biological reactiveness. A differentiation between temporary microbiomes, for the production of bio-fabricated materials, and permanent microbiomes, for extended biological reactivity, which in turn demand a structural substrate, as seen in Biota Lab's project Computational Seeding of Bioreceptive Materials, can thus be identified.

Textiles and fibrous materials display many features which make them very suitable as a medium for an active textile microbiome. A single yarn manufactured from natural plant fibres usually consists of entwined individual fibre segments. Due to the specific manufacturing process, the micro structure of an individual yarn displays a very high surface-to-volume ratio. At the same time it is permeable by liquid and air while having the ability to retain a high moisture content over extended periods of time (Fidelis et al. 2013). Furthermore, the cellulose content of natural fibres can be metabolised by some microorganisms, thus promoting their growth (Callewaert et al. 2014). Their internal microstructure consists of arrays of channels

Mycelium material manufacturing

https://blog.drupa.com/de/mushroom-packaging/

(Image redacted for copyright reasons)

Figure 71 Mould is filled with inoculated loose substrate

Mycelium brick

https://www.wired.com/2014/07/a-40-foot-tower-made-of-fungus-and-corn-stalks/

(Image redacted for copyright reasons)

Figure 72 Fully colonised brick, mycelium matrix permeates and solidifies the substrate (lumens) permeating the fibre, while the morphology of the outer surface structure contains channels and pores generating a large surface area (Figure 74) (Fidelis et al. 2013). Synthetic fibres such as polyamide, in contrast, possess a uniform surface and a solid core (Figure 75) (Liu et al. 2018). Their morphology usually only offers a minimal surface area while their internal structure is neither permeable nor interspersed with channels (Figure 75). Besides their special material fibrous constitution on a micro scale (Figure 73), fibrous materials systems possess a unique versatility when it comes to their application for construction. As discussed in the previous chapters, both tensile membranes and rigid and load-bearing composite components are possible. At the same time, textiles can either remain soft after manufacturing or can be solidified using post-manufacturing processes. In contrast to granular substrates, as applied in the Hi-Fy project (Benjamin 2017), or solid substrates, such as the bioreceptive concrete structures of the Biota lab (Cruz & Beckett 2016), textiles allow for various geometries and morphologies which are unique to the field of textiles. These characteristics offer a distinct spatial potential for construction strategies.

Illustration of structural hierarchies of bamboo

Bioinspired structural materials (Wegst et al. 2015), p.27

(Image redacted for copyright reasons)

Figure 73 Hierarchical organization of bamboo fibres (Wegst, Bai, Saiz, Tomsia, and Ritchie, 2015)

Plant fibre SEM microscopy

The effect of fiber morphology on the tensile strength of natural fibers (Fidelis et al. 2013), p. 152

(Image redacted for copyright reasons)

Figure 74 Plant fibre SEM microscopy, cross-section (Fidelis et al. 2013)

Polyamide fibre microscopy

Preparation and characterization of polyamide 6 fibre based on a phosphorus-containing flame retardant (Liu et al. 2018), p. 9269

(Image redacted for copyright reasons)

Plant fibre SEM microscopy

The effect of fiber morphology on the tensile strength of natural fibers (Fidelis et al. 2013), p. 154

(Image redacted for copyright reasons)

Figure 75 Left Polyamide fibre microscopy section and surface (Liu et al. 2018)

Figure 76 Right Plant fibre SEM microscopy (Fidelis et al. 2013)

5.5. Biomic explorations

The previous chapter suggested that fibrous materials can carry distinct microbiomes which might even differ in relation to their origin, material and fibrous micro structure.

The following exploration observes the activity of four different intrinsic textile microbiomes of natural fibres - cotton, hemp, linen viscose and jute. The untreated fibres were placed in a sterile agar Petri dish (Figure 77) and incubated over ten days at ambient temperature. Pictures were taken after two, five and ten days (Figure 78 - Figure 81). Their microbiological activity during the incubation period clearly demonstrates the biomic activity and agency of natural fibres. Once placed in the optimal conditions of the Petri dish, dormant micro-organisms autonomously start metabolising, multiplying and expanding.

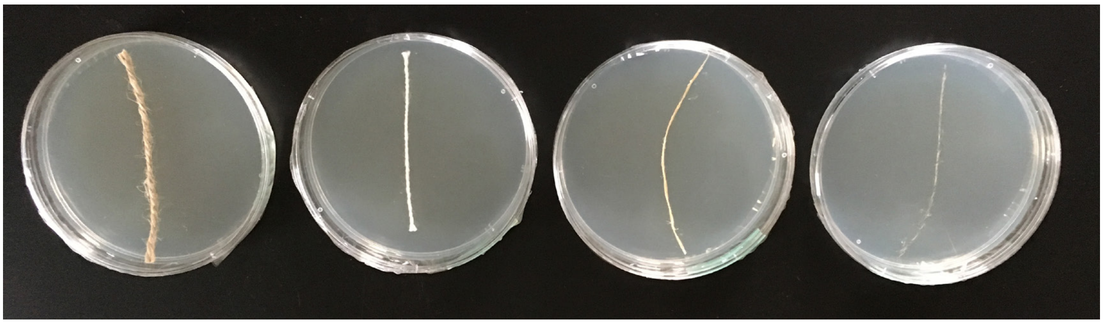


Figure 77 exploration setup; fibres, petrishes day 0

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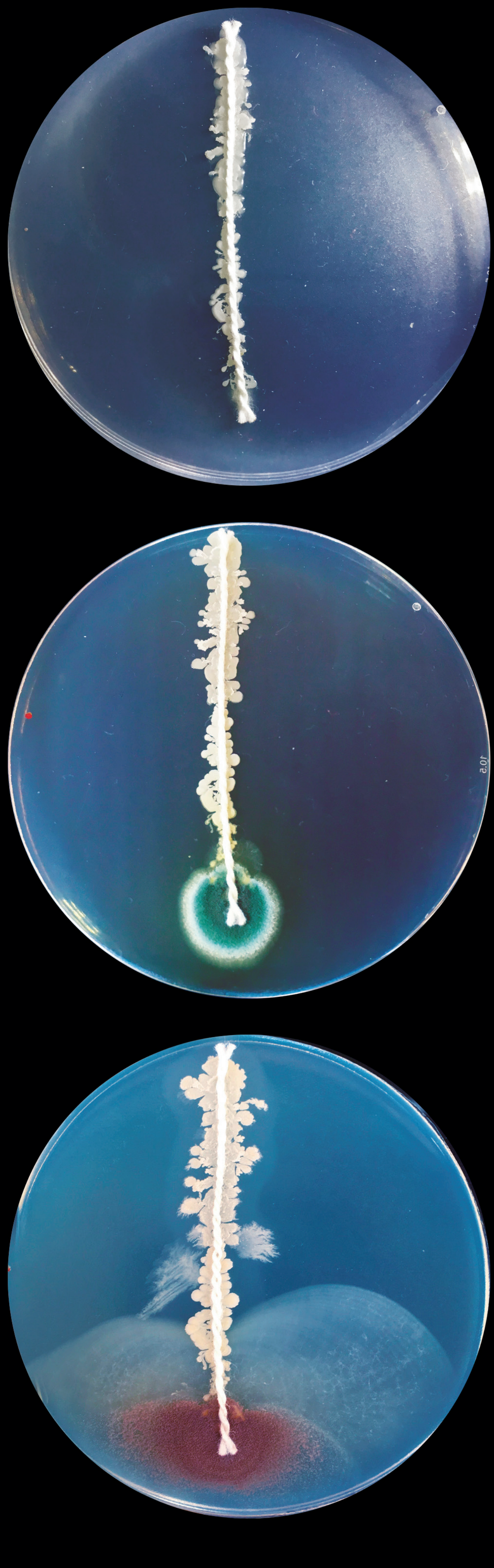
Figure 78 textile microbiome cotton

Figure 79 textile microbiome hemp

Figure 80 textile microbiome linen viscose

Figure 81 textile microbiome yute



5.6. The spatial potential of textile substrates

Besides their biological, structural and morphological characteristics, as outlined in the previous sections, textiles inherently possess distinct potential to define and generate space. Within a Cartesian system a point is defined by three specific coordinates in three axes – x, y and z. Connecting two points generates an axis. By adding another point, a spatially defined plane is created, which, by adding another axis, produces a three-dimensional space, defined through four points and three axes. A single filament tensed between two points can be understood as an axis within a given space. By merely adding two additional filaments or axes a spatial configuration emerges, defined by the distinct geometry of the textile system.

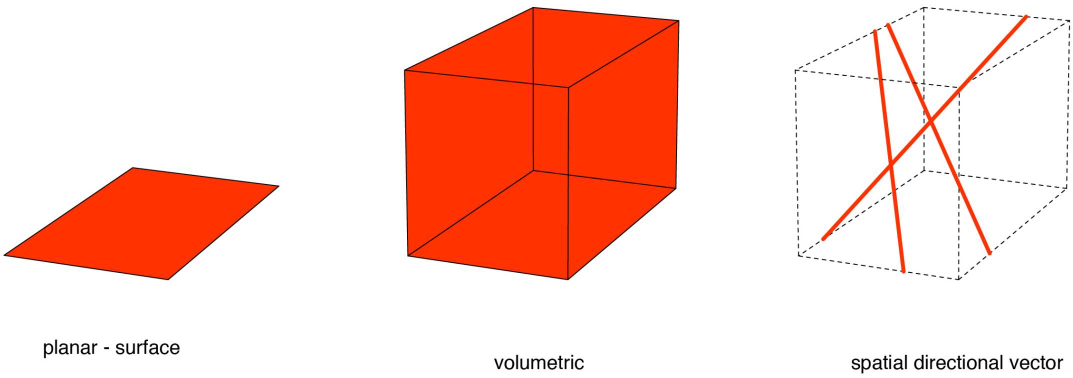


Figure 82 Spatial potential of textiles compared to planar and volumetric approaches

Artists and designers such as Thomas Saraceno and Fred Sandback make use of this relatively simple strategy to define and create spaces which could not have been constructed with conventional building materials (Figure 83) (Figure 84). These examples showcase the unique spatial potential of textile systems.

A rich vocabulary of textile-specific operations can be applied to generate distinct spaces and shapes. Sandback, for example, creates minimal spatial configurations by tensing threads between defined points within a given space. Similarly, Saraceno works with spatially defined start and end points, creating additional nodal points, however, through knotted intersections of the filaments. While Sandbacks's method creates linear arrays, Saraceno's strategy enables an increased geometrical complexity.

Akira Ikeda Gallery installation

http://www.akiraikedagallery.com/pe_FredSandback_berlin.htm

(Image redacted for copyright reasons)

Figure 83 Fred Sandback, Akira Ikeda, 2011

Thomas Saraceno installation, Venice 2009

https://www.cairn.info/revue-etudes-2018-12-page-111.htm#

(Image redacted for copyright reasons)

Figure 84 Thomas Saraceno, Galaxies Forming alongside Filaments, like Droplets along the Strands of a Spider's Web, 53rd Biennale di Venezia, 2009

While Sandbacks's and Saraceno's installations can be categorised as soft textile structures, similar strategies are applied in the context of composite winding, especially the case studies discussed earlier (ICD/ITKE Research Pavilions and Turm 2). Their manufacturing approach similarly utilises the distinct "soft manufacturing" of textile or filamentous structures through textile processes – in these cases composite winding, which generates a tensile structure. In a second step, however, the geometry is immobilised through a resin matrix, adding compressive strength to the tensile structural system.

More complex textile operations include techniques such as knitting, weaving or braiding. These textile processes allow for multi-hierarchical structures and customised features, such as pockets or channels, structural gradients or complex shapes (Figure 85 , Figure 86).

Harnessing these potentials for an active textile microbiome combines the potentials of both domains- textiles and microbiology- creating bio-active and spatial textile scaffolds.

5.7. Biotechnology, society, architecture

As outlined previously, every textile material innately is home to myriad of active or dormant microorganisms. However, controlling and designing such a microbiome enables to embed distinct biological features within textile materials while maintaining the same material and manufacturing system.

We are now just starting to understand the complex relationship we have with microbiology. Microorganisms are inevitably part of our lives, and not merely responsible for disease and infection (Strachan 2000). Meanwhile, it is widely accepted that our human microbiome has a reasonable influence on our health and psychological constitution (Cryan & O'Mahony 2011). The practice of trying to modify and enhance this relationship with probiotic supplements and specific diets is currently fashionable (Stamatova & Meurman 2009). In contrast to merely using microbiology to refine food products, this new trajectory aims to modify the human body by embracing and even designing a symbiotic relationship with microbiology.

The built environment offers multiple stages for various (micro)biological processes to take place which can influence architecture and also its inhabitants. Confined, dense urbanism can affect human health due to unsanitary conditions, polluted drinking water or the lack of waste removal, where various microbiological hazards can emerge (McMichael 2000). These conditions, combined with dense population, allow epidemics to spread. Diseases such as the Black Death or Spanish flu found ideal breeding grounds in crowded city environments.

Modern city planning and architecture, combined with modern hygiene, however, have contributed to the diminution of microbiological hazards. The infrastructure underlying modern

Knitted tensile membrane

http://www.materialarchitectures.com/social-sensory/

(Image redacted for copyright reasons)

Figure 85 Knitted tensile structure, detail (Sean Alquist)

Knitted installation MoMA PS1

https://www.archdaily.com/805580/jenny-sabin-studio-selected-as-winner-of-the-moma-ps1-2017-young-architects-program/58a6c6e1e58ecefe50000187-jenny-sabin-studio-selected-as-winner-of-the-moma-ps1-2017-young-architects-program-image

(Image redacted for copyright reasons)

Figure 86 Knitted spatial textile structure "Lumen", MoMa PS1 2017 (Studio Jenny Sabin) cities conveniently supplies us with fresh water and provides a hygienic waste management system. The rise of modernity, with its clean, sleek, sanitised materials and surfaces, promises transparent, efficient, clean, hygienic architecture (Cruz 2013). Natural forces and biological processes (except for the purpose of human nurturing and entertainment) are seemingly strictly excluded from the interior and merely have the function of entertainment. Climate control, light and constant monitoring provides the ideal environment for human habitation. Having learned from history that specific built environments can contribute to the development of biological hazards, an increasingly mysophobic architecture has developed over the last century. The human body and its habitat are perceived as a sanitised entity, seemingly disconnected from any microbial activity (Cruz 2013).

This perception contrasts starkly with the natural evolution of the human body within its environment. A human is an intrinsically symbiotic organism which has co-evolved in and with a certain microbiome. Simultaneously, certain microbiomes developed around the human species. Through this distinct intertwinement of different biomes, the human species evolved into a "super-organism" in which the human body and its associated biomes became inseparable (Parker 2010). Due to rapid changes in our behaviour, diet and hygiene since the industrial revolution, as well as the impact of modern cityscapes and infrastructures on our lives, this balanced relationship shifted. The Biome Depletion Theory (Rook et al. 2003) suggests that exposure to a variety of active and diverse microbiomes is crucial for developing a resilient immune system. Furthermore, the theory argues that the modern shift in our relationship to, and acceptance of, microbiomes in general is responsible for the rise of allergies, autoimmunity disorders and even appendectomy surgery (Parker 2010). The trend towards a controlled and sanitised built environment not only changes our relationship with the biomes but also affected the biome itself. The increased use of sanitisers (such as isopropanol-based liquids) has resulted in the gradual adaptation of certain pathogens towards these measures. Recent research showed that certain strains of E.faecium obtained in 2015 show mutated DNA in comparison to older strains from 1997, which makes them more tolerant of exposure to isopropanol-based sanitisers (Pidot et al. 2018).

The study of multi-resistant pathogens suggests that bacteria can even exchange specific genes responsible for certain resistance towards antibiotics amongst different strains (Tenover 2001). These examples illustrate in a rather intimidating way that the microbiome surrounding us cannot be treated as a stain or dirt which can be wiped away instantly. Instead, it is an adaptive and responsive interface comprising an inter-dependent and communicating microbiota which influences human life in complex and intelligent ways. Modern technology and design help to inhibit the outbreak of dangerous epidemic or pandemic diseases and infections (for now), through modern means of hygiene and cleanness.

The conception that microbiology within the built environment is inevitably connected with our idea of filth, dirt and danger persists, and is informed by historical epidemic or pandemic events etched in society's collective memory. This connotation is a significant driver which inhibits the potential for microbiology to be used in a beneficial way for the built environment. The past has significantly shaped our perception of microbiology, therefore, the contemporary discourse has to break with antiquated concepts and distinguish between passive dirt or filth and an active living system such as a microbiome.

This argument does not advocate for a less hygienic built environment but rather a new awareness towards an informed differentiation between a pathogenic and a beneficial microbiome. While microbial activity in any form is currently not compatible within the conventional modern perception of architecture or architectural materiality, we might see a shift in future architecture as it embraces a more symbiotic relationship. In a similar way to current developments in the context of the human microbiome, where we are starting to understand its complex functionality, the built environment microbiome might experience a similar paradigm shift in the future.

As well as reframing the role and importance of microorganisms, if these are applied in the context of design we similarly have to acknowledge their distinctive design agency. Biological systems are inherently complex and operate in a different domain from that of conventional materials (Benjamin 2018). An engineering approach alone will reach its limits when confronted with biological complexity. Even if engineering and architecture developed diverse approaches to simulate biological phenomena such as growth, they still remain a reductionist abstraction (Zolotovsky 2017). This inability to fully control outcomes and processes requires a certain commitment from the designer to work with the distinct agency of biology (Armstrong 2016). We can observe such a mindset by looking at the methods and work of biologists, brewers or cheesemakers, who have learned how to present a "stage" for biology to act on and know when and how to interact with their "collaborator". Bio-design and Bio-fabrication in the architectural domain asks precisely for this "stage" to be set in a spatial and aesthetic context. The idea of the active textile microbiome contributes to the field by providing a spatial scaffold which becomes the mediator between space, structure and biological agency. It sets spatial boundary conditions and bridges the scalar gap between the world of microbiology and architecture while providing a blank canvas for the biological system to act upon.

Biological systems operate and act dynamically and seemlessly between micro, macro and meso scales hence provide an inspiring paragon. A tree provides an ideal example on a structural and performative level. The folowing paragraph outlines possible strategies for translating these features into the architectural domain.

6. The Tree

An inter-scalar performative and tectonic role model

6.1. Introduction

> "But an irregular world tries to compensate for its own irregularities by fitting itself to them, and thereby takes on form" (Alexander 1964, p.15)

A tree is an example of a natural organism which provided, most probably, the first natural composite material humans engaged with in the context of early construction. Its use for tools dates back 400,000 years (Radkau 2012). Besides its importance as a material for tools and construction, its use as fuel for fire was equally important for the advancement of humankind (ibid, 2012). Wood as the raw material for paper had, and still has, significant importance for recording and transmitting knowledge.

Besides their practical value as a source of wood, trees contribute significantly to CO_2 absorption and oxygen generation. The underlying principle, as shared with other biological organisms, is their distinct metabolism. This mechanism equally accounts for the generation of its structural tissue on a micro level and through its iconic morphology (Barnett & Jeronimidis 2003). While acknowledging that the following generalist overview will not account for a trees holistic complexity and all its variety -over 80.000 species have been documented (Barnett & Jeronimidis 2003) – the following short section will outline the most relevant characteristics in the context of the research. These outlined characteristics are, in contrast to what the categorisation might imply, interdependent and in constant flux.

1. Metabolism

A tree metabolises nutrients and water from the soil it grows in, and through photosynthesis (an anabolic form of metabolism) it translates light energy into chemical energy, thus achieving growth. Its metabolism varies over the seasons, which manifests in growth rings and (in some species) a yearly renewal of its canopy. A tree's unique biological performativity even establishes symbiotic dependency, emerging through the "collaboration" with other natural organisms (Stamets 2005). Furthermore, due to the organism's immobility, it sources all the resources needed for its maintenance and expansion directly from its immediate environment, providing the ultimate blueprint for sustainable construction.

2. Global geometry and topology

A tree presents a highly elaborate and complex geometry which not only varies from species to species but is similarly dependent on environmental factors, nutrient levels and landscape topology. By this means the tree adapts locally to the increasing self-load through the expansion and optimisation of its structural system. At the same time, the overall geometry similarly reacts to external loads, such as wind, through the adaptation of its topology, as well as its geometry. This process is in constant flux, negotiating the distinct parameters (such as nutrients, light, loads) to achieve an optimum with the least energy and material effort.

3. Structural gradient on micro scale

As outlined previously a tree is an example of a complex structural system which, utilising only three main materials (cellulose, hemicellulose and lignin), optimises and iterates its internal and external structure in accordance to its environment. The formation of *reaction wood* provides a glimpse into the inherent structural complexity of a tree.

Wood mainly consists of three components arranged in "a microfibrillar skeleton of cellulose enveloped by hemicellulose molecules organized as successive ribbon-like structures, with lignin occupying the empty spaces left between the hemicellulose molecules." (Barnett & Jeronimidis 2003, p.68). Cellulose and hemicellulose are fibrous elements, while lignin can be understood as the binding matrix, accounting for structural rigidity. The organism, as a first step generates a fibrous scaffold ("skeleton") which then is successively reinforced through the lignin matrix. This microstructure adapts through a change in internal geometry as well as material composition, related to structural loads and self-weight. Reaction wood describes the distinct adaptation of wood, which can be found in cantilevering branches or in areas with directional wind forces. In this way the tissue adapts locally by increasing the cellulose (fibrous) constituent on the tensile forces (the top of the branch) while increasing the lignin content to improve the compressive strength (the underside of the branch) (Barnett & Jeronimidis 2003).

Here, internal, geometrical, structural and chemical optimisations occur locally to reinforce and stabilise the wood structure, delivering an almost unnoticeable (from the outside) but significant structural improvement (Barnett & Jeronimidis 2003). This effect accompanies the optimisation of the global geometry, presenting a multi-hierarchical strategy for a functionally graded material and optimised geometry on a micro and macro level.

4. Fibrous structural strategy

The distinctive way to generate composite materials, where a soft microfibril scaffold is gradually reinforced through lignin deposition, is one of the possibilities the study of a textile microbiome could offer. The use of a textile substrate enables a plethora of geometrical, spatial and tectonic possibilities on almost every scale. This form-giving momentum can be utilised to provide, like the microfibril skeleton in wood, a scaffold which determines the spatial edge-conditions for a secondary bio-colonisation. This spatial bioactivity can, for example, result in a gradual deposition of a bio-derived reinforcing matrix.

The aim of the following investigations is not to approximate a tree in its full complexity but to use some of the characteristics described as a blueprint for investigations and strategies for the generation of fibre-based composites. Wood as an intrinsically hierarchical material exemplifies how materials can be optimised through structural hierarchies. Textile composites can in this context provide a platform which is similarly hierarchical. The interdependency between fibre, textile structure, directionality and matrix enables an interaction at every scale to influence global behaviour.

The following part of the research is concerned with the practical implication of the activation of a composite matrix through a textile microbiome. Employing active microorganisms as potential matrix materials shifts the notion of an active matrix to a metabolising matrix. The focus is on exploring the outlined structural strategy utilising three distinct microorganisms while simultaneously exploring the infrastructural demands of such a culturing process.

Wood SEM microscopy

https://botweb.uwsp.edu/anatomy/images/dicotwood/pages_c/SEM0231new.htm

(Image redacted for copyright reasons)

Figure 87 Graded and multifunctional wood microstructure (white oak) (Curtis, Lersten, Nowak 2002)

Wood print

https://thehudsonco.com/news/2016/1/29/the-ming-bryan-nash-gill-the-hudson-company

(Image redacted for copyright reasons)

Figure 88 Trunk crosssection, topologically optimised shape and internal structure (Brian Nash Gill)

6.2. Etudes

Each étude[16] encompasses a comprehensive overview of established work in the field, as well as an introduction to the relevant organism and its distinct properties. Furthermore, the chosen setup is discussed and a set of hypotheses for each étude is drafted. The results of the individual small-scale projects are then analysed in relation to the initial hypotheses in order to inform a large-scale demonstrator (Figure 89).

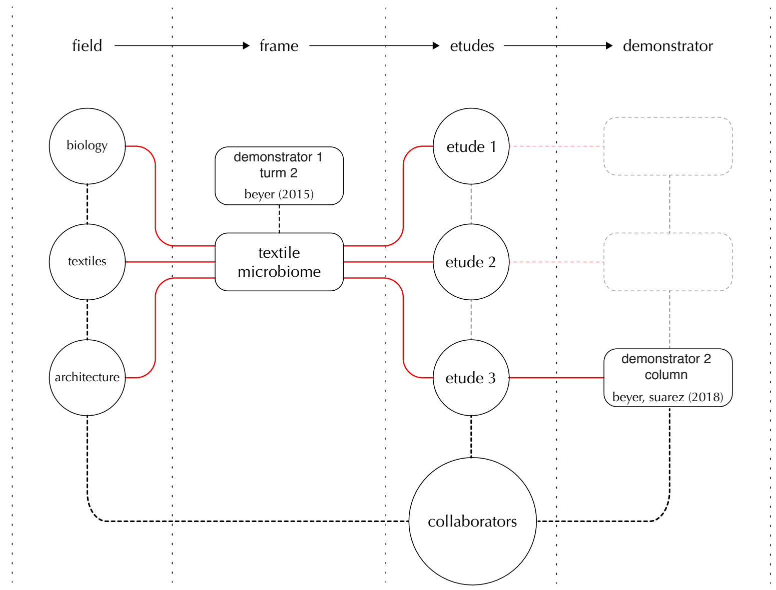


Figure 89 etude structure

6.2.1. Etude 1 *Pleurotus Ostreatus*

The following étude explores strategies for textile-based, spatial configurations of mycelium-based composites. The application of a biologically active textile material to a passive scaffold investigates the time-based development, as well as the performative aspects, of mycelium-based composites.

Context

Pleurotus Ostreatus is a common edible mushroom, widely known as an oyster mushroom. The fruiting body of the fungus, which is also the part of the organism with the most iconic appearance, is widely popular for its culinary use. It typically develops above the growing medium (soil, wood, etc.) and can appear in a wide range of morphologies, with diverse shapes resembling hats, lamellas or sponges which contain spores to be released in order to spread and multiply the organism (Gow & Gadd 1995). The fruiting body, commonly recognised as the

16 Further information on the notion of the etude in the context of this research is provided in appendix H

Mycelium growth pattern and fruiting body

http://jncc.defra.gov.uk/images/natsoln_fungal_mycellium_forestorganics%20-web_v_Variation_1.jpg

(Image redacted for copyright reasons)

Figure 90 Mycelium and fruiting body

Mycelium micro-structure

http://www.liverpoolartslab.com/wp/2018/08/22/the-march-of-the-mycelium/

(Image redacted for copyright reasons)

Figure 91 Mycelium microstructure attached to substrate mushroom, is however only the most visible part of the whole organism of a fungus. It emerges from a complex living network, called mycelium (Figure 90).

Whereas the temporarily forming fruiting body is the way in which the fungi procreates, the filamentous mycelium network is understood as the permanent, vegetative organism whose medium proliferates in search of nutrients (Stamets 2005). It is comprised of a gradually propagating network of chitinous filaments which are in constant exchange with their immediate environment (Figure 91). The mycelium system digests externally the organic media it permeates by emitting enzymes and acids on a micro scale to its immediate environment while absorbing the dissolved nutrients (Stamets 2005).

Through this process, the network generates zones of nutrient depletion, and therefore has to relocate to access unused resources, which results in the expansion of the network (Gow & Gadd 1995). This expansion or growth results in a filamentous matrix permeating the organic medium. In contrast to plant matter, which is based on cellulose and lignin, the mycelium develops a chitin-based cellular structure (Travaglini et al. 2013).

A fungus is understood as a modular organism, which means it develops through the repeated iteration of its modular constituents in a branching pattern. Each module of the hyphae (part of the mycelium matrix) possesses every attribute to reproduce and survive independently of the larger network it is derived from.

Unitary organisms, such as humans or mammalian animals, in contrast possess highly specialised cell arrangement, forming distinct organs like arms, legs, heart and brain (Gow & Gadd 1995). Although these organs function in a very complex and interconnected way within the biological system of the human body, they cannot sustain their function by themselves and cannot reproduce any missing organs (In other words, a single finger will not regrow the hand it needs to function).

The general dichotomy of the two biological systems can also be observed through their approach towards sensing their environment to source nutrients. In the case of human or mammalian animals, understood as unitary organisms, a highly specialised strategy enables the whole organism to physically relocate through its physiological features, such as legs and arms, sensing its environment through specialised, unique organs such as eyes, ears or the nose.

The fungus, as a modular organism, employs a different strategy, which is best described as redundancy and emergence. Even though the organism cannot relocate through physical movement like an animal or human, its distinctive ability to multiply from

Mycelium growth pattern

Network organisation of mycelial fungi (Fricker et al. 2007)

(Image redacted for copyright reasons)

Figure 92 Mycelium growth patterns of different strains (Fricker et al. 2007)

Installation Mycotectural Alpha P. Ross

https://inhabitat.com/phillip-ross-molds-fast-growing-fungi-into-mushroom-building-bricks-that-are-stronger-than-concrete/philip-ross-mycotecture-1/

(Image redacted for copyright reasons)

Figure 93 P. Ross Mycotectural Alpha (2009) a single module enables it to relocate through expansion within a given medium (Figure 92) (Gow & Gadd 1995).

The organism's expansion and relocation is therefore driven through a combination of hydro- and chemotropism (movement/expansion related to moisture and chemical/nutritional stimuli) (Horan & Chilvers 1990), which implies that the organism does have an intrinsic ability to sense its environment and act accordingly, which can, according to Stamets (2005) be understood as a distinct feature of fungal intelligence and emergent behaviour.

Furthermore, the fungal network employs a process called autophagy, which is triggered through stress factors such as nutrient depletion or changes in environment (e.g. humidity). An autophagic process within organisms generally describes the process of recycling nutrients from unused cell material (Pollack et al. 2009). This process indicates that the fungal network not only expands according to external stimuli such as humidity and nutrients, but also employs a feedback mechanism to monitor the overall health of the network, resulting in an active restructuring process in undersupplied areas while steering its activity towards more promising areas for expansion (Fricker et al. 2007).

The (relative) simplicity of its cells enables rapid multiplication, enabling it to permeate and therefore sense large volumes for nutrients. These networks are highly adaptable and can be established or redirected upon damage (Stamets 2005). Unlike plants, the fungus draws the entire energy needed for its development from its medium; it is therefore not dependent on a light source or other forms of external energy or nutrient supply. At the same time it can process and propagate a wide range of organic substances and by- and waste products, such as wood, straw, grains or even used ground coffee (Hebel & Heisel 2017). This adaptivity and responsivity connected with its redundant network and its modular growth accounts for the organism's resilience.

Besides its biological characteristics, the chitin filament network which permeates the medium, gradually builds up a substructure or matrix which leads to an adhesion of individual granular particles, thus altering the global mechanical behaviour of the medium, which has been explored in the context of sustainable construction (Figure 93) (Travaglini et al. 2013; Benjamin 2017; Heisel et al. 2017). The mycelium-solidified materials produce lightweight structural materials with similar properties to Styrofoam, but completely biodegradable and non-petrochemically derived. They are highly insulative and buoyant, as well as flame retardant (Travaglini et al. 2013).

Two main factors in particular account for the low environmental impact of the material. First, various agricultural by-products can be used as a potential substrate (Heisel et al.

2017). This utilises waste materials as well as enabling the local sourcing of raw materials (Benjamin 2017). Second, as outlined previously, the material demands no additional chemical binding agents. The material is held together solely by a dense mycelium matrix which develops through the nutrient exchange between the medium and the living organism. The development of the mycelium occurs within approximately a week in an ambient temperature, without the need for external energy or nutrients. As discussed above, the fungus is a modular organism, which means that only a small amount of starter culture is needed to trigger the development of mycelium.

In order for a (mono)culture of fungi to thrive on a specific medium, it has to be sterilised. One method of achieving this is through an autoclaving process, which deactivates any prevailing microorganisms on the medium through heat treatment. The sterilised medium then undergoes an inoculation process, in which an active culture is mixed with the medium. This ensures that the fungal culture has no (microbial) competition inhibiting the colonisation process. The technology is very accessible, as the tools needed for the inoculation of a substrate can be found in every kitchen and a very basic knowledge of microbiological culturing techniques is sufficient to carry out small-scale experiments.

The material gained momentum within the design community after Philip Ross, amongst others, started to work on the topic in the 1990s, developing what was later termed mycotecture (Terranova & Tromble 2017). Ross's Mycotectural Alpha project at the Kunsthalle Düsseldorf (2009) is composed of wood fibre blocks solidified by a mycelium matrix, arranged in an arch-like structure, and resembles a structural system held together solely by the structural capacity of a mycelium matrix.

David Benjamin advanced this principle into a large-scale pavilion, the Hy-Fi Tower, realized for MoMA's PS1 in 2014. In this, a tailor-made brick system allowed the construction of a 13-metre-tall tower. Both examples illustrate the successful application of the material in an architectural context and demonstrate its sufficient load-bearing capacity for large-scale applications. The Hy-Fi Tower project also proved that an outdoor application is possible and that the material was completely biodegraded after dismantling (Benjamin 2017).

The individual bricks were fabricated using a mould-based process. The inoculated substrate, based on agricultural by-products, was put into the moulds. Subsequently the fungus then gradually permeated the substrate, establishing a mycelium matrix that bound together the loose material. The substrate, in this case, forms the reinforcing, discontinuous phase of the composite material, whereas the permeating mycelium structure renders the continuous phase, or matrix. The process of filling the moulds (with the fungus-inoculated substratum) does not take into account the fibre direction of the individual particles of the substratum, so the finished product can be understood as a unidirectional composite material. The material can, from a mechanical viewpoint, be classified as a cellular material (open cell foam) (Travaglini et al. 2013).

In order to use a mycelium-based composite as a directional composite material, the control of the internal fibre direction and hierarchy has to be anticipated. The Mycelium Tectonics project (Figure 94) (Tabellini 2015) employs directional fibre arrays which are gradually propagated by an active culture of *Pleurotus Ostreatus*. The project illustrates the morphogenetic potential of an active microorganism within a textile structure (Figure 94). The structure was arranged in a predetermined geometry and inoculated with an active fungus culture.

Over the course of several days a filamentous mycelium substructure was established between the individual (substrate) fibres. It could be observed that the mycelium substructure influenced the fibrous configuration in different ways. Most apparent was that the mycelium covered the fibrous structure in a white network of mycelia hyphae, which gave the scaffold an almost monolithic appearance. This effect can be ascribed to the minimal surfaces generated through the mycelium substructures between the fibres (Figure 95).

With the Mycelium Tectonics project, Tabellini (2015) provided an inspiring example of the morphological potential of fungal structures and their agency within a textile scaffold. Based on this project, a setup was developed which attempted to apply this method to a winding setup based on the logic of the Turm 2 project (Beyer 2015) to investigate the potential for an in-situ application of the method.

Besides the difference in geometrical approach, the distinction between the two setups can be seen in their inoculation strategy. Tabellini (2015) applied a textile structure within a rigid substructure prior to inoculation. Whereas this approach provides greater control for small-scale prototyping, it also necessitates the autoclaving of the whole structure before the fungus culture can be applied. As autoclaves have a very limited volume, Tabellini's approach is therefore restricted to small-scale structures.

Mycelium growth on textile scaffolds

Mycelium tectonics, Tabellini (2015) p.147

(Image redacted for copyright reasons)

Figure 94 Mycelium Tectonics; Tabellini (2015)

Mycelium growth on textile scaffolds, detail

Mycelium tectonics, Tabellini (2015) p.151

(Image redacted for copyright reasons)

Figure 95 Mycelium Tectonics, Detail; Tabellini (2015)

Hypotheses

The following process employs a textile material which has been inoculated and incubated before its application to the substructure. This method provides several advantages in terms of applicability in the context of larger-scale structures and potential on-site use-cases. With regard to the sterilisation process of the substrate in particular, a rigorous technique is essential to reduce the risk of potential contamination to a minimum. Once the medium is colonised, its susceptibility towards contamination decreases significantly, and the material can be applied in a semi-sterile environment. Tabellini's (2015) approach is bound to a certain volume and geometry, which is dependent on the autoclave dimensions. The following scenario proposes a semi-finished material, produced prior to its implementation, which can theoretically be applied in a broad variety of shapes and configurations using textile fabrication methods.

Initial tests have shown that a solely fibrous substrate does not provide enough nutrients for the organism to propagate.[17] The approach investigates a hybrid approach, employing a porous textile tube to contain a mixture of wood fibres and oat bran to sufficiently supply the organism with nutrients and moisture. At the same time, better structural performance was anticipated as a result of the increase in the tube diameter (tube vs single thread).

Hypotheses

1. A substratum-filled tubular textile can be inoculated with a *Pleurotus Ostreatus* strain and support the development of the culture over an extended period of time, thus establishing a fungi-based microbiome on the textile-based material.

2. The pre-application inoculation and incubation process enables the application of the material in a semi-sterile environment and reduces the potential for contamination.

3. The material can be applied using winding methods (see La Magna et al. (2014), Beyer (2015), Knippers & Koslowski (2017)) with a continuous material system. The microorganism will, solely through the formation of a mycelium structure, successively alter the structural behaviour of the system.

17 In Tabellini's example the fibres are treated with an agar/nutrient mixture

Figure 96 Removable modular plexiglass substructure

Protocol

A series of initial substratum samples were tested for familiarisation with the technique and to determine the optimum moisture content and substratum composition. For the textile tube a flax yarn was selected, as the flax yarn presented good knit-ability on a 12-needle tubular knitting machine. Furthermore, it presents a sustainable and bio-degradable alternative to synthetic materials such as nylon or polyester. The substratum consisted of an 80:20 mixture of oak sawdust and wheat bran.

The optimum moisture content was determined by visually comparing the mycelium development (Figure 98 - Figure 100). The best results were achieved with a moisture content of the substratum of 20% .Subsequently, a continuous tube 8m long was produced and filled with the substratum. The autoclaving of the material was undertaken at a temperature of 120ºC for a period of 60 minutes.

After the sterilisation process the material was cooled to room temperature and a liquid culture of *Pleurotus Ostreatus* was used to inoculate the substratum. The incubation period of seven days resulted in the full colonisation of the material (Figure 101).

After this, the material was applied to a substructure consisting of transparent acrylic material (Figure 96 Figure 102). The substructure determined the specific location of the nodal crossing points of the substratum. The application process was undertaken by hand in a semi-sterile off-lab environment. During the manual manipulation the fragile layer of mycelium on the outside of the material which developed during the incubation was damaged. A further incubation period of 10 days at room temperature was required for the fungus to fully colonise the structure, rendering a white fibrous structure (Figure 106).

Figure 97 Substrate composition tests

Figure 98 Optimal mycelium development

Figure 99 High water content; accumulation in the lower section

Figure 100 Contamination; mould development (marked red)

Figure 101 Substrate incubation process

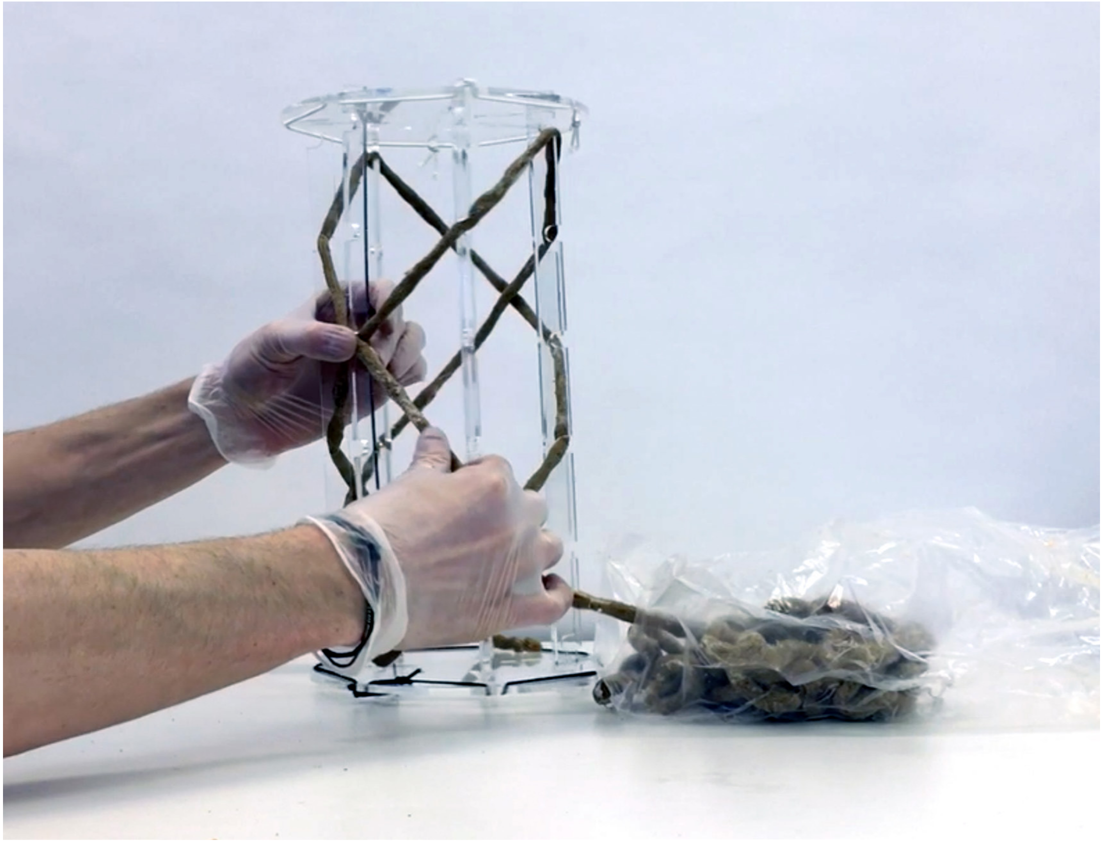


Figure 102 Manual substrate application onto scaffold structure

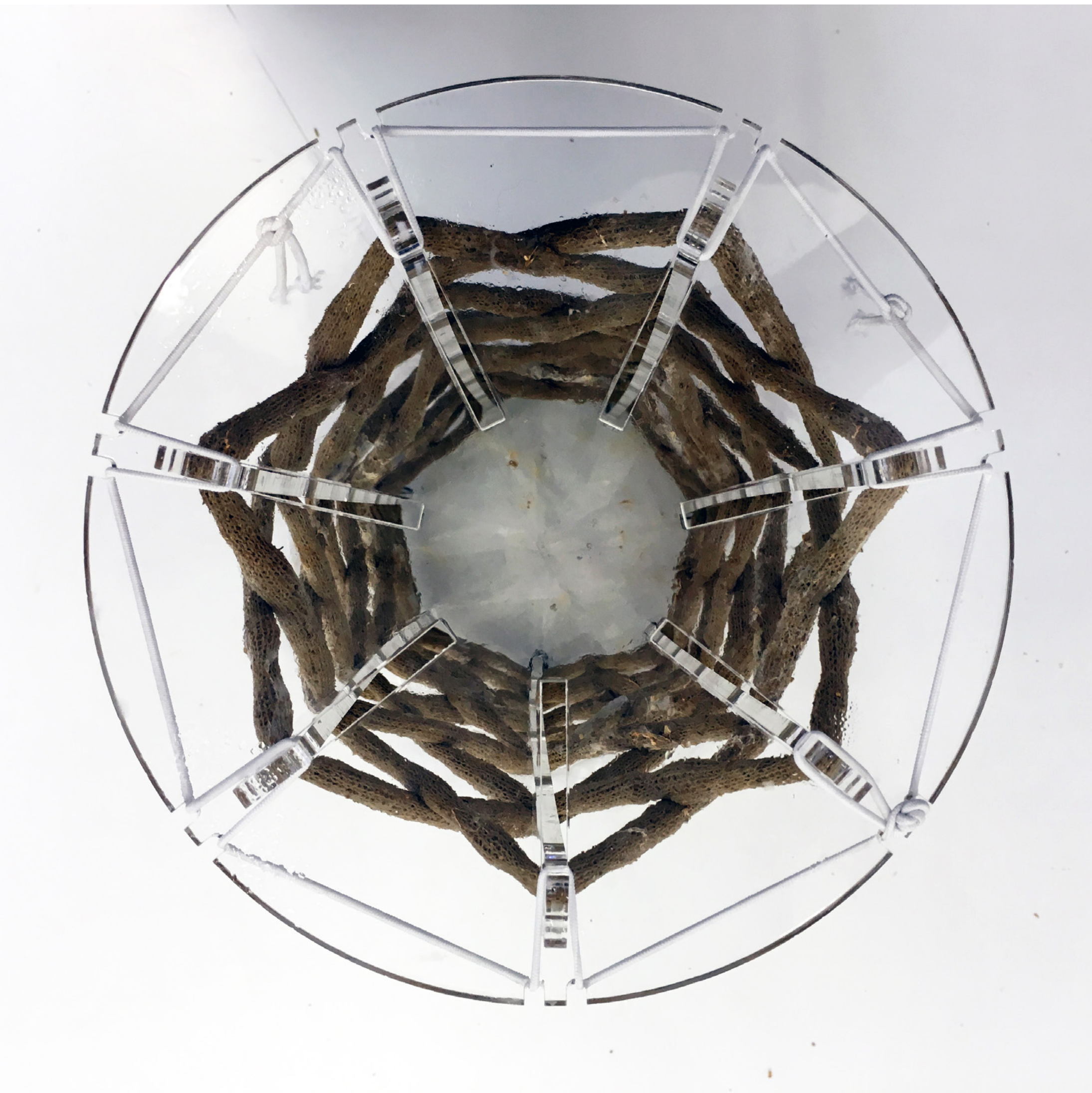


Figure 103 Top view scaffold with substrate

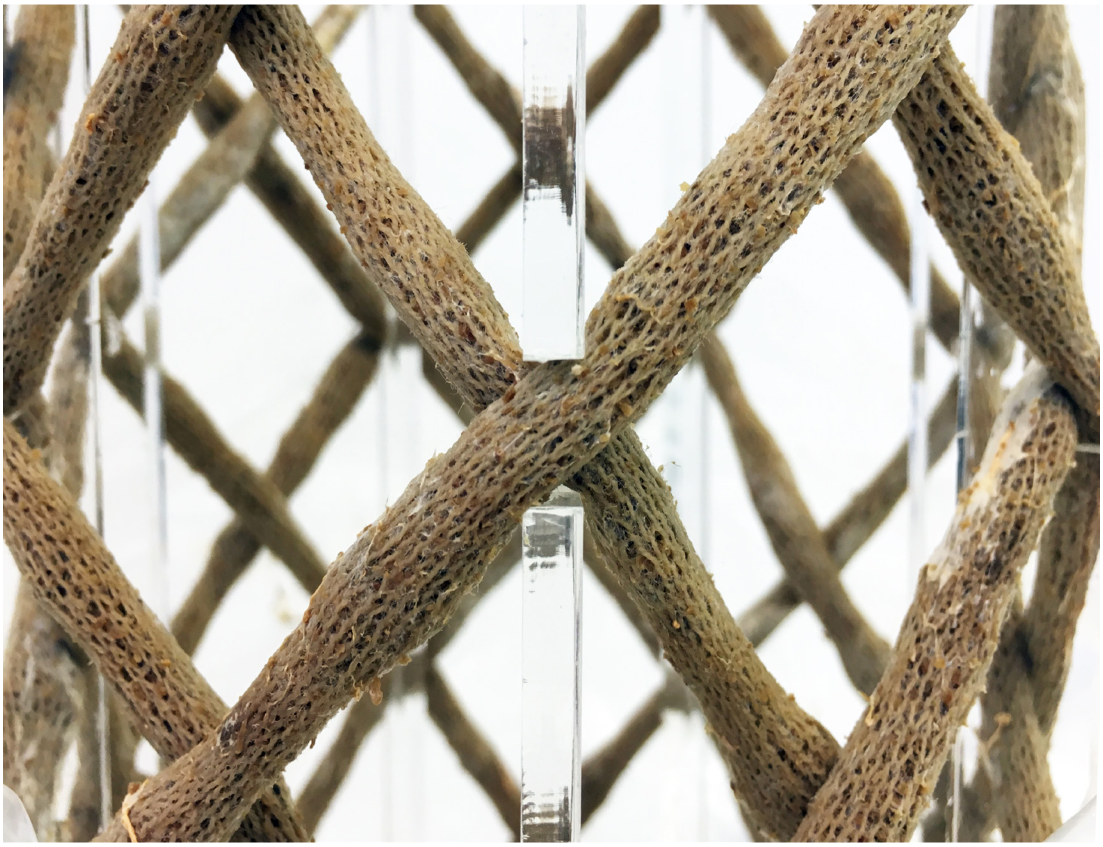


Figure 104 Substrate on scaffold: day 1, detail

Figure 105 Substrate on scaffold: day 7, detail

Figure 106 Substrate on scaffold: day 7

Assessment

Etude 1 delivered valuable insights for working with mycelium-based materials. The hands-on approach, with its direct results, helped to mediate expectations and also unfolded the various challenges of sterile workspaces, culturing living organisms and also the public response to the project.

As Etude 1 was executed in the semi-public space of a university research studio, the setup unintentionally also became a design probe for a specific audience. The sterile working methods, resembling the aesthetic of the medical field rather than a design process, triggered several adverse reactions from fellow students and staff. At the same time, the unconventional appearance and handling of the material evoked the interest of many people. However, these reactions were not directly quantified or analysed; they served as a reminder that potential architectural materials cannot be decontextualised. They are inherently embedded within a social context, which is further evidence of their complex nature.

Furthermore, the setup enabled reflection on the hypotheses outlined earlier:

Hypothesis 1

1. A substratum-filled tubular textile can be inoculated with a *Pleurotus Ostreatus* strain and support the culture's development over an extended period of time, thus establishing a fungi-based microbiome on the textile-based material.

Successful colonisation of the substratum was achieved on the textile-based medium within one week. Damage to the mycelium network on the substratum occurred during the manual application to the scaffold, but regrew within a week, thus illustrating the self-regenerating characteristics of mycelium. An active mycelium development, with no further supply of nutrients, could be achieved within two weeks.

Hypothesis 2

2. The pre-application inoculation and incubation process enables the application of the material in a semi-sterile environment and reduces the potential for contamination.

The pre-application inoculation has proven to be a suitable strategy for applying the substratum in a semi-sterile environment. After the medium was left in sterile conditions for a period of five days, to fully colonise, it was handled in a semi-sterile indoor environment with no major contamination occurring. During the following incubation period on the scaffold, only a marginal contamination of the medium could be identified, to which the fungus responded by actively encasing it in mycelium (Figure 108).

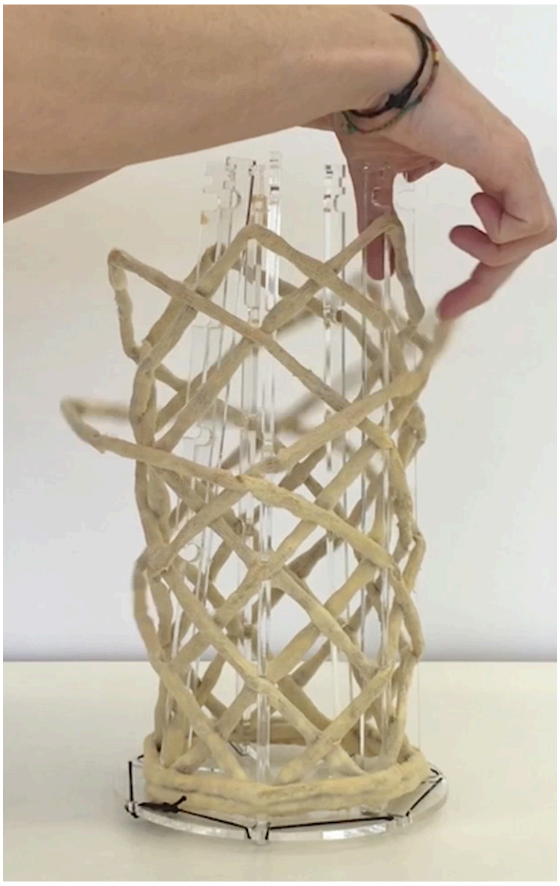


Figure 107 Collapsing structure after scaffold removal

Figure 108 Contaminated area (red)

Hypothesis 3

3. The material can be applied using winding methods (see La Magna et al. (2014), Beyer (2015), Knippers & Koslowski (2017)) with a continuous material system. The microorganism will, solely through the formation of a mycelium structure, successively alter the structural behaviour of the system.

The removable acrylic scaffold incorporated a series of recesses on its vertical sections, which were used as guides for winding of the substratum. This setup determined the final geometry and subsequently generated overlaps between the subsequent windings. After applying the substratum, and during the incubation period on the scaffold, the organism adapted to the geometrical reconfiguration of its medium. The weakened mycelium network, partially damaged through the reconfiguration, re-established healthy growth. The nodal points, which are of significant importance for establishing a structural system, were successfully merged by the mycelium matrix (Figure 105). The setup was able to successfully apply a winding technique to a textile-based mycelium substratum while maintaining its biological activity during the whole process. Furthermore, a merging effect through the natural expansion of mycelium could be observed on overlapping or crossing segments of the array.

After the incubation period the structure was successively air-dried over a period of three days. While it maintained its shape during drying, with the substructure still in place, the structure could not maintain its shape and structural integrity when the scaffold was removed, which resulted in the collapse of the structure. Individual segments, however, displayed an increase in stiffness compared to the non-treated material, which indicates that the mycelium matrix induced a change in structural performance locally, although not on a global level. The reason for the inconsistent behaviour could relate to the heterogeneous density of the substratum filling. Mycelium in general is able to bridge and fill certain gaps within a medium; however, these gaps present potential weak points within the material system, which pose a risk of fracture.

Discussion

Although earlier material tests on a smaller scale were undertaken, Etude 1 was the first setup which incorporated a spatial configuration based on a textile logic. This involved the inoculation and incubation of a substrate and the manual application to a substructure for further incubation.

Due to the controllable properties and predictable behaviour of conventional materials such as resin and fibres, their application on site does usually not cause any issues. However, for biologically active materials any change of environment triggers a microbiological reaction and can, depending on their sensitivity, influence their behaviour or cause potential contamination with other cultures.

The early stages of the culturing of fungal mycelium, in particular, pose a high risk of contamination. As indicated earlier, Tabellini (2015) counteracted this risk by sterilising the whole setup, thus providing a very controlled environment, which, however, inhibits the applications of structures which exceed the volume of the autoclave. The pre-culturing and successive application of the substratum, as demonstrated in Etude 1, potentially allows for larger-scale applications and on-site application in a semi-sterile environment, due to the reduced risk of contamination.

A further iteration would need to improve the material consistency and homogeneity of the filler medium in order to avoid weak points within the structure, and therefore maintain stability. Even though the nodal crossings were merged through the mycelium, they could not sustain a connection during the occurrence of sheer force. A second winding layer would thus enhance the connection through the mechanical bond (as a result from a further layer on top) which, in combination with the binding properties of the mycelium, could result in increased stability.

6.2.2. Etude 2: *Acetobacter Xylinum*

The following étude investigates Incubation scenarios for the cultivation of bacterial cellulose on fibre-based textile scaffolds for the generation of directional composite materials. The aim is to test and compare two incubation methods for an *Acetobacter Xylinum*-based textile microbiome.

Context

Bacterial Cellulose (BC) has received increased attention in the field of sustainable design (Hemmings 2008) with projects such as Suzanne Lee's "Bio-Couture", creating a leather substitute, or Jannis Huelsen's approach to "growing" a small-scale chair in his Xylinum project (2011) (Figure 112). The material is generated solely through bacterial metabolism, and can be grown using natural and abundant resources such as household sugar and vinegar. Providing sustainable alternatives to petrochemically based materials and animal-derived products, its potential applications include leather or plastic substitutes (Lee et al. 2014). At the same time, it is a very versatile raw material with potential applications ranging from medical implications and active filter membranes (e.g. Customem Ltd.) to composite materials (Qiu & Netravali 2014). Bacterially derived cellulose has a high level of purity and can be generated within days, in comparison to plant-derived cellulose, which takes from months to years to be ready for harvest. The bacterium *Acetobacter Xylinum* (AX) generates BC in a liquid culture by metabolising glucose-based nutrients (Figure 110). The BC network accumulates in form of an aerogel which consists of BC, water, nutrients and active bacteria usually on the surface of the culture (Lee et al. 2014).

The common method for cultivation is a surface culture (Figure 109). The BC-based hydrogel forms on the surface of the inoculated nutrient solution and can therefore be easily extracted and then processed (Lee et al. 2014). The cultivation in trays using surface cultures results in a flat material. However, expanding the growth into the third dimension enhances the material's potential for various design applications and reduces the post-processing.

Huelsen (2011), for example, applied a patented coating technology developed by Jenpoymer (2011) to a model for a chair. In this instance a predetermined geometric volume was colonised with a bacterial treatment and incubated over several days. During incubation, BC developed around the volumetric scaffold. After the BC development the scaffold was removed. This process demonstrates the rather time-consuming and intricate process of developing a 3D BC shape. Furthermore, it constrains the geometric potential due to the use of volumetric scaffolds (Figure 112).

Kombucha surface culture

https://ideas.ted.com/the-skirt-and-shoe-made-from-kombucha/

(Image redacted for copyright reasons)

Figure 109 Surface culuture (Suzanne Lee)

Bacteria and cellulose fibres microscopy

Guided Growth - Design and Computation of Biologically Active Materials (Zolotovsky, 2017) p.63

(Image redacted for copyright reasons)

Figure 110 Acetobacter Xylinum nano cellulose fibre generation

The following étude attempts to explore alternatives to this approach by proposing a textile-based form-giving method. Textile scaffolds enable a range of geometric operations, and can therefore contribute to the development of 3D BC growth.

At the same time, it is intended that the textile scaffold should integrate into the BC matrix and therefore increase its structural performance, resulting in a textile-based BC composite material while avoiding a complex internal scaffold (Figure 113).

BC-coated fibres have been investigated as a sustainable alternative to synthetic composites and resins, and show huge potential for further development (Pommet et al. 2008). Most of the reviewed research projects (Pommet et al. 2008, Lee et al. 2014;) focus on the micro structure and performative properties of the material, and incorporate multidirectional fibrous mats.

Etude 2 investigates the inoculation and incubation of directional, spatially defined fibre structures with an AX-based microbiome (Figure 111). For the individual setups, distinct incubation methods were chosen to determine their influence towards the microbiome and the resulting material.

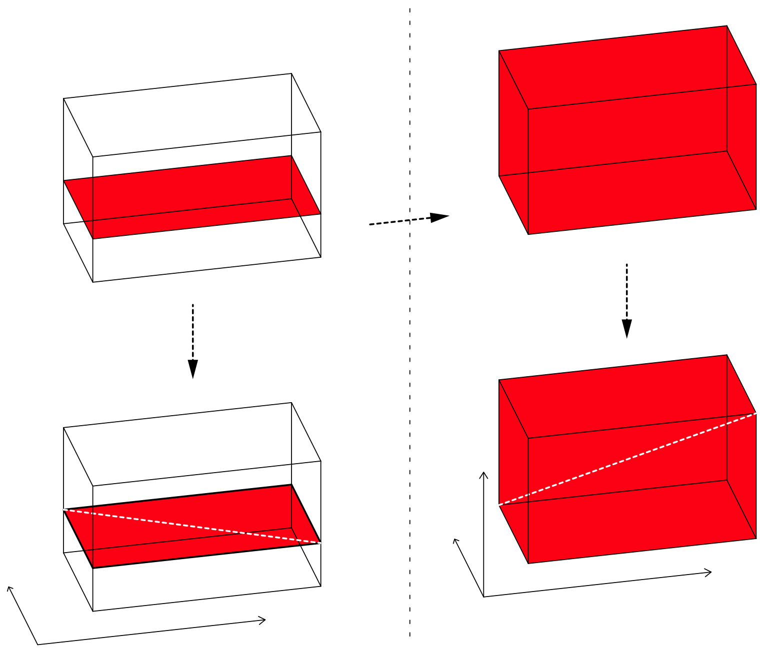


Figure 111 from 2D surface culture to 3D surface independent incubation

Bacterial cellulose chair model

http://www.jannishuelsen.com/?/work/xyliumstool/

(Image redacted for copyright reasons)

Figure 112 Chair (Huelsen 2011)

Fibres embedded in bacterial cellulose

http://www.iaacblog.com/programs/bio-fabric-microbial-cellulose/

(Image redacted for copyright reasons)

Figure 113 IAAC fibre integrated in surface culture (2016)

Specimen

The specimen consists of a polypropylene raft (B) onto which the AX-inoculated yarn is mounted (A) (Figure 114). The setup allows the investigation of the behaviour of AX on a yarn with a defined direction. It simultaneously creates two areas of interest, a straight segment (C) and an area of intersection (D). The different setups employ the same specimen configuration for the purposes of comparison.

The following plant fibres were tested in the different setups:

- Hemp
- Sisal
- Cotton
- Nettle
- Banana fibre

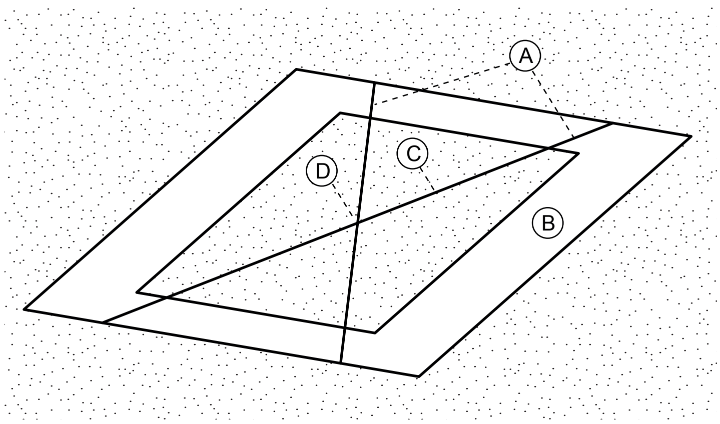


Figure 114 Specimen raft

Nutrient Solution:

The solution[18] was prepared by boiling 2 litres of water, green tea and 200g of sugar for 15 minutes and adding 200ml of vinegar after cooling.

Inoculation of specimen:

An active culture of AX was processed in a blender (1min, 2500w) to generate a homogeneous AX bacterial solution. In order to inoculate the yarn, it was immersed in the solution for around 30 seconds. The active AX solution permeated the fibrous structure of the yarn, thus establishing an active AX-based microbiome. However, the following setups differ in the way the yarn is incubated; they follow the same protocol for the inoculation process, as well as for the preparation of the nutrient solution. The protocol was executed in a semi-sterile and off-lab environment.

Incubation

Conventionally AX is cultivated in flat trays, with the BC forming on the interface between the liquid culture and the air, resulting in planar sheets (Lee et al. 2014).

However, various other forms have developed to generate BC at scale (Islam et al. 2017) of which some introduce either agitated nutrient liquids or moving systems which allow for the incubation of three-dimensional objects.

In the context of étude 2, three scenarios were selected which are potentially suitable for treating textile scaffolds. Setup 1 introduces a conventional planar, surface culture in order to determine the behaviour of AX on different textile substrates. Setup 2 and 3 incorporate technically more complex systems which allow a three-dimensional treatment.

Setup 2 is based on a rotary disc contactor which employs a rotating substructure onto which the samples are mounted (Islam et al. 2017). This setup allows the specimens to alternate constantly between the nutrient fluid and the air. Due to the rotation, samples with increased geometric complexity can be incubated.

Setup 3 employs a strategy utilising ultrasonic vaporisation to disperse the nutrient fluid within a bioreactor (Hornung et al. 2007). This system was developed by Hornung et al. (2007) to increase the speed of growth, as well as the quantity of BC generated and, similar to Setup 2, extends the incubation space into the third dimension.

18 After Bio-Couture protocol (Suzanne Lee, http://www.ecouterre.com/grow-your-own-microbial-leather-in-your-kitchen-diy-tutorial/ 23.02.2015)

Objectives and Hypothesis

During, as well as after, incubation the specimens underwent a visual assessment to evaluate whether the AX-based microbiome responded to the incubation with BC development. Furthermore, the aim was to observe the ability of AX to actively foster adhesion between singular yarns through a biologically derived BC-matrix.

The setup aims to evaluate the following hypotheses:

1. An active AX-based textile microbiome can trigger the formation of BC within a textile structure, thus influencing its structural behaviour through a BC matrix.

2. Rotary, e.g. aerosol-based, incubation strategies (Setup 2/Setup 3) enable a non-planar incubation of AX-based textile microbiomes.

For each setup, five days of incubation were allocated, followed by an air-drying process and a visual assessment and analysis of the specimens. Furthermore, a comparison of the incubation methods, as well as the behaviour of the different fibre types, provided an overview of the parameters and potentials of process and material.

Setup 1: Surface culture

The setup (Figure 115) consisted of a static and sterile nutrient solution within an enclosed tray with a filter mounted on top to allow for gas exchange.

The specimens (B) acted as rafts due to their plastic frame, which maintained their flotation on the nutrient solution (A).

As BC usually forms on the interface between the nutrient solution (A) and the air (C) the flotation is vital for the formation of BC on the specimens (Lee et al. 2014).

The specimens were incubated for five days while maintaining the nutrient solution at a temperature between 25-30ºC.

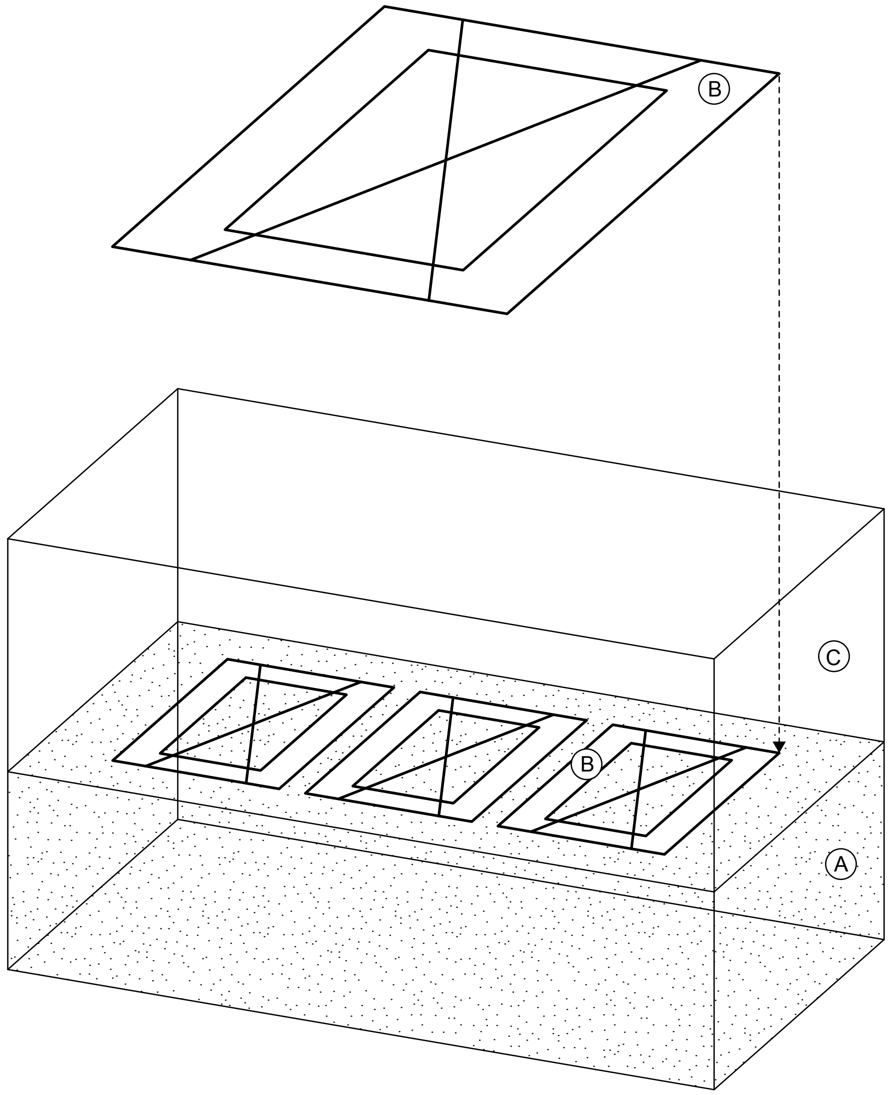


Figure 115 Static culture incubation

Setup 1: Results

Setup 1 incorporated the cultivation of a BC-based textile microbiome in a static surface culture. Figure 117 shows the specimens after five days of incubation, floating on the nutrient solution. All the specimens show clear signs of developing BC alongside the textile scaffold, in the form of a white translucent gel. The BC developed in a heterogeneous pattern alongside the scaffold, as indicated in Figure 117 area B (Figure 118). Although small differences relating to the growth patterns of the BC can be recognised, the visual examination suggests that the overall development of the BC has not been significantly influenced by the type of fibre used.

It could be observed that the BC growth was initiated by the inoculated yarn and gradually colonised before it spread into the adjacent nutrition solution (Figure 117 , area C). Area A (Figure 117) remained uncolonised, as a result of the frame impeding contact with the air.

During the incubation period the BC covered the scaffold while embedding the yarn in a cellulose matrix which, after the drying process (30ºC, 12h), solidified and significantly increased its rigidity. As the BC Aerogel consists of up to 98 per cent water (Qiu & Netravali 2014) a decrease in volume was observed during the drying.

The tests demonstrated that BC developed on the surface of the nutrient solution. Due to the floatation of the specimen the fibres integrated with the BC matrix. However, the integration of the textile scaffold differentiated between the two sides (Figure 116, Figure 123 , Figure 124). It can be assumed that this is due to the single-sided exposure to air. Microscopy (Figure 125 - Figure 128) illustrates the fibre integration within the BC matrix. As outlined previously, the fibre material did not influence the BC development; however, Figure 127 and Figure 128 suggest that the coarse hemp yarn generates an increased interface surface, which improves its adhesion to the matrix (A,B,C: fibrous interface to BC).

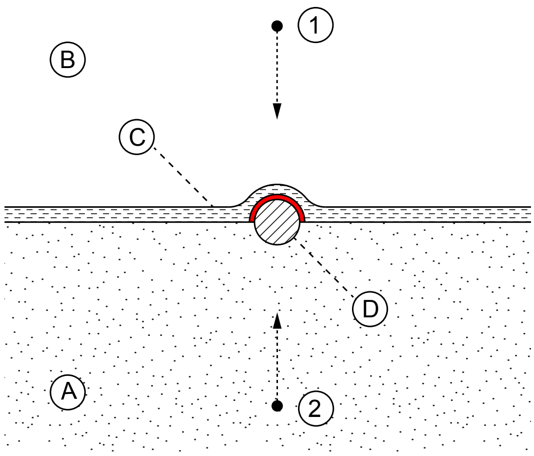


Figure 116 Schematic section, BC adhesion detail

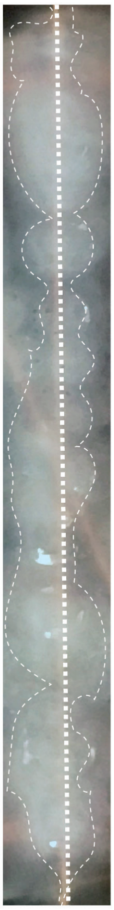


Figure 118 Magnification of BC growth pattern, area B

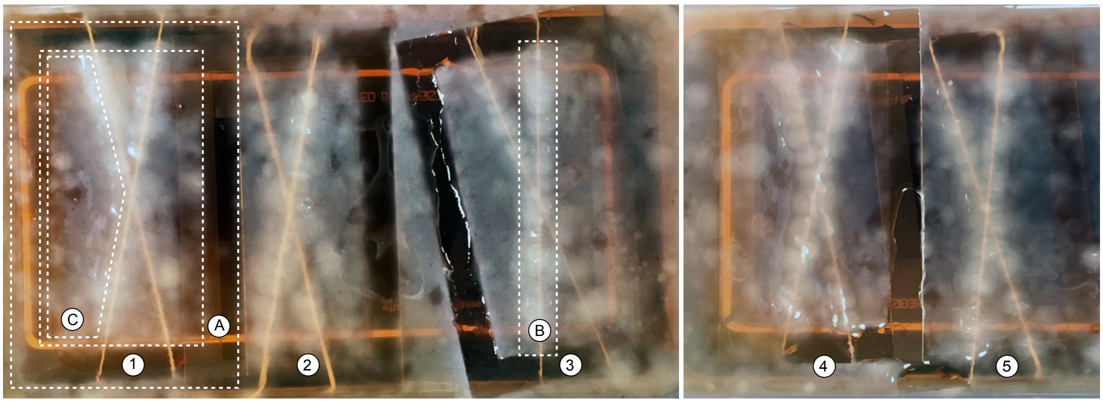


Figure 117 Incubated specimen, day 5

Figure 119 Wet BC specimen

Figure 120 Translucency of BC specimen

Figure 121 Underside BC specimen

Figure 122 Upside BC specimen

UNDERSIDE

UPSIDE

Figure 123 Dried specimen; underside

Figure 124 Dried specimen; upside

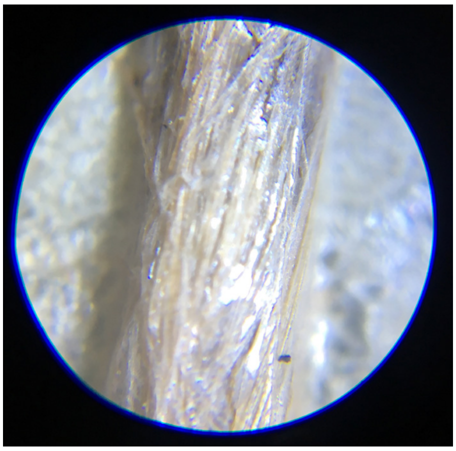


Figure 125 60X Magnification

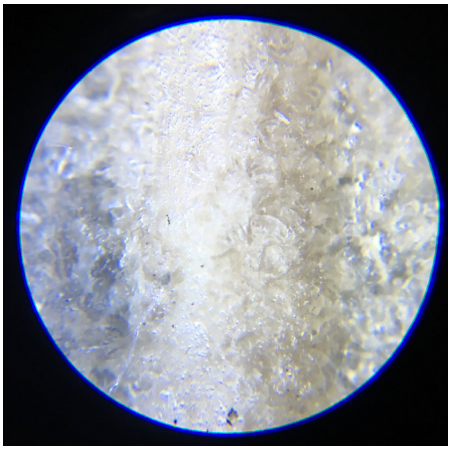


Figure 126 60X Magnification

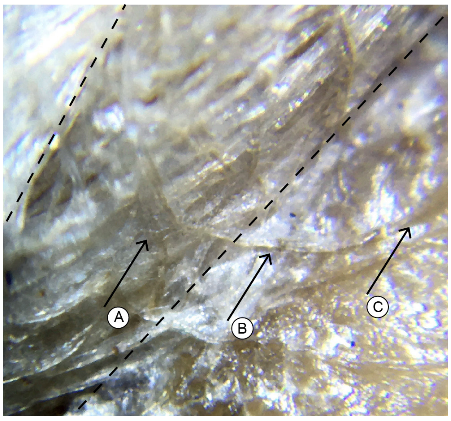


Figure 127 100X Magnification

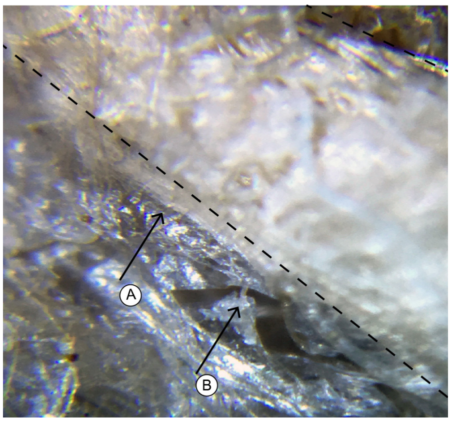


Figure 128 100X Magnification

Setup 2: Rotary incubation method

Setup 2 (Figure 129) investigated a incubation method inspired by a rotary disc contactor incubator (Islam et al. 2017). Through constant rotation (B), the samples (C) constantly alternated between submersion in the nutrient suspension (A) and the air. During Setup 1 it could be observed that BC formed not only on the textile substrate but also in the adjecent nutrient solution. Furthermore, Setup 1 only enabled a planar formation of BC while leading to differentiated development between top and bottom. This setup aimed to increase the homogeneity of the BC formation while simultaneously limiting the development of BC to the textile substrate. Simultaneusly the setup was intended to investigate wheather this incubation method would potentially allow for larger and more complex substrate geometries.

Setup 2: Results

Setup 2 enabled the incubation of an AX-based textile microbiome independent from the nutrient suspension surface. The development of BC occurred mainly alongside and within the textile scaffold (Figure 132 Figure 134). Some samples, however, displayed an irregular BC development and/or BC formation also in the intermediate space between the textile scaffold (Figure 134). Furthermore, the visual examination of the BC formation suggests that, as seen in the results of Setup 1, the yarn morphology and the surface area influences the BC development more than the type of material.

The rotary incubation system successfully initiated a surface-independent BC development on a textile scaffold. Although, the resulting BC deposition was sparser and less consistent than that in Setup 1, the BC matrix, was able to bond the two yarns at their crossing point. Employing the setup for a more complex textile structure seems feasible, but demands a reiteration of the technical setup in relation to issues of reliability and structural capacity.

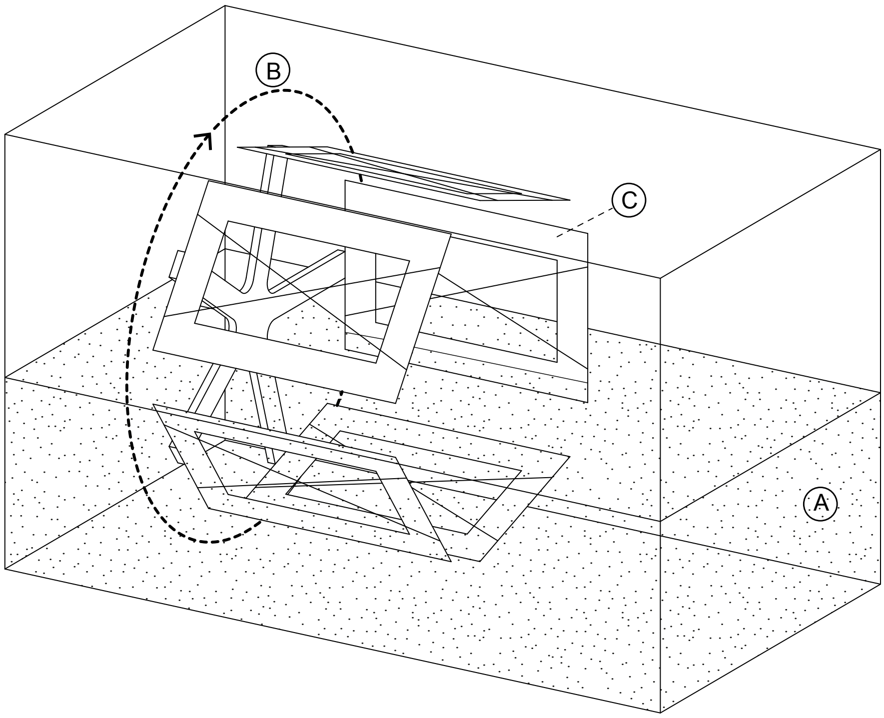


Figure 129 Rotary incubator

Figure 130 Specimen setup before incubation

Figure 131 Specimen setup after incubation (5 days)

Figure 132 Specimens after incubation with BC development

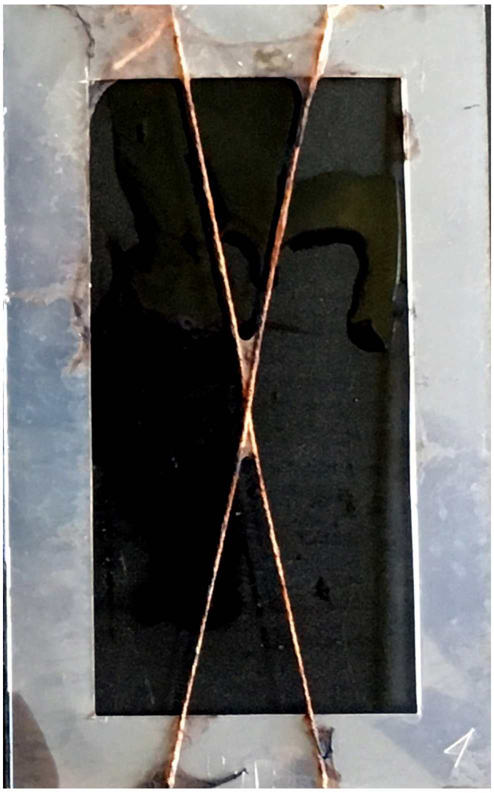


Figure 133 Incubated sample (thin sisal), detail

Figure 134 Incubated sample (hemp), detail

Setup 3: aerosol-based incubation

During Setup 2 it was found that the constant agitation of the samples resulted in a non-homogeneous deposition of BC. Furthermore, the moving parts of the setup presented additional potential for failure.

The following method (Figure 137) employed aerosol-based nutrients, providing a three-dimensional incubation space (E) which enabled a static mount of the sample. The aerosol was generated by an ultrasonic vaporiser (B). During initial testing it was found that due to the heat emission (40-50ºC) of the vaporiser, the incubator (E) and the nutrient tank (A) had to be spatially separated. Therefore the Incubator and the nutrient tank are connected through two pipes (D), which allow the aerosol (C) to flow from the upper tank to the lower tank by means of gravity while maintaining their spatial separation and allowing the aerosol to cool to around 30ºC. The specimen (F) is mounted in the incubator (E) and continuously immersed in the nutrient aerosol. The system did not rely on mechanically moving parts, therefore providing a very reliable and low-maintenance setup.

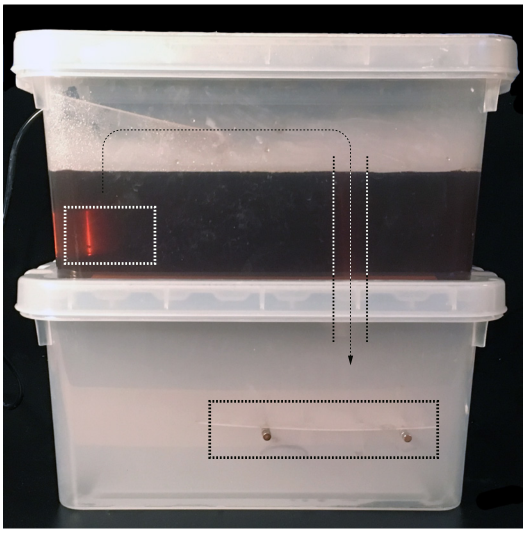


Figure 135 Aerosol culture setup

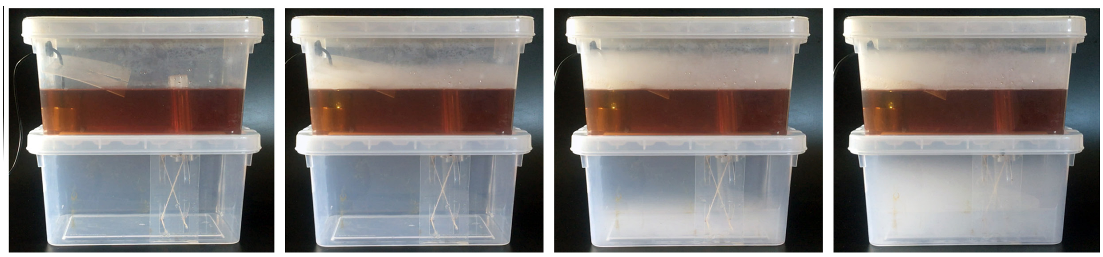


Figure 136 Aerosol dispersion in incubator setup

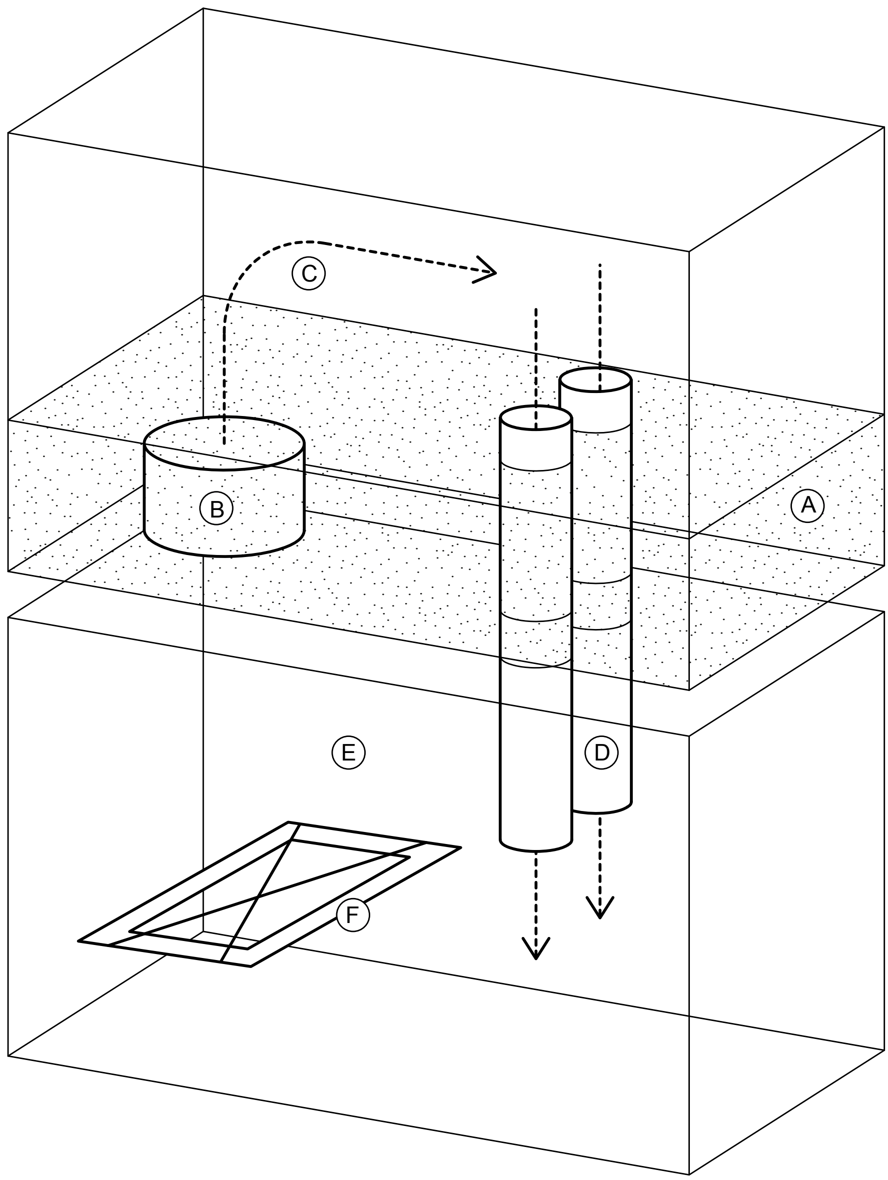


Figure 137 Aerosol culture setup design

Setup 3: Results

Based on Setup 1 and the finding that the yarn material does not influence the development of BC, the next setup employed hemp yarn alone, which, due to its coarse finish, provides a large surface for BC to adhere to. The frame holding the yarn in place was slightly altered to maintain an unrestricted flow of vapour around the sample. The orientation and geometry were not, however, affected by this change.

The specimen was incubated over a period of five days while constantly maintaining exposure to the vaporised nutrients (Figure 136).

Figure 140 and Figure 141 show the development of BC within the textile scaffold before and after treatment. It mainly occurs on areas of intersection (1) as well as the yarn mounting (2). The nutrient aerosol condensed on the specimen and accumulated primarily around these areas, which explains the enhanced BC formation.

In comparison to the other setups, Setup 3 generated the lowest BC yield; however, microscopy (Figure 138) showed that the BC formed a consistent and homogeneous layer around the fibre (Figure 139). The low yield suggested that the nutrient solution might have to be adjusted, due to the use of aerosol instead of liquid, in order to enhance the BC formation.

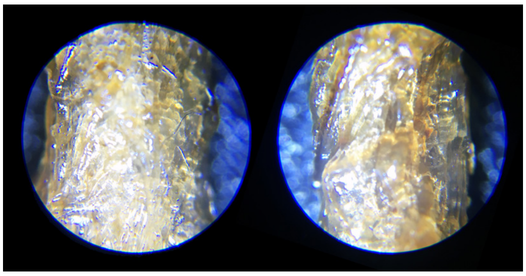


Figure 138 . BC development on aerosol incubate yarn, 60x magnification; left: viewpoint 1; right: viewpoint 2

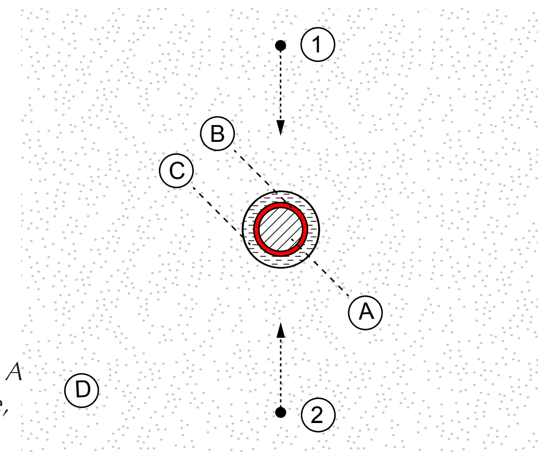


Figure 139 BC formation morphology in Setup II, 1 and 2 microscopy viewpoints: A fibre, B fibre interface, C BC, D aerosol

Figure 140 . Specimen before incubation

Figure 141 . Specimen after incubation (5 days)

Discussion

Etude two investigated three different incubation methods for an AX-based textile microbiome. The different setups enabled the validation of the hypotheses outlined in the beginning.

1. An active AX-based textile microbiome can trigger the formation of BC within a textile structure, which influenced its structural behaviour through a BC matrix.
2. Rotary, e.g. aerosol-based, (Setup 2/Setup 3) incubation strategies allow for a non-planar incubation of AX-based textile microbiomes.

All three setups demonstrate the formation of BC triggered by an active AX textile microbiome. Setup 1 provided the most the effective method for BC generation; however, it was restricted to a one-sided BC development due to the geometrical restrictions of a surface culture. Setup 2 incorporated a rotary strategy, which allows for non-planar incubation independent from the interface between the nutrition solution and the air, which extends the potential geometrical possibilities of AX-based microbiomes. However, the results achieved with the setup did not produce homogeneous and consistent results. Setup 3 produced the most homogeneous results and allowed for a static and non-planar incubation. However, the setup yielded the lowest BC deposition of all the setups.

The dried BC matrix bonded the individual yarns at their intersecting points while stiffening the whole textile scaffold. However, the samples in their dried stage became very brittle and were liable to break. Three-dimensional structures and potential post-treatments such as resin impregnation, however, could improve the behaviour of the material (Huelsen 2011).

A further test was undertaken with Setup 2, and a more complex textile scaffold (Figure 142 Figure 147 which departed from the aim to generate a homogeneous deposition and, further, explore the potential of the rotary system for non-deterministic formations of BC. The outcomes show that the various BC formations occurred within and between the scaffold. This system demonstrates that the resulting BC structures were formed through the activity of the AX-based microbiome and the distinct BC morphology generated in response to the constant rotation. Thus the BC materials formed on the scaffold in a specific state of equilibrium dependent on gravitation, fluid dynamics and the geometry of the scaffold.

While the sample did not respond well to structural loads, it demonstrated the unique agency of the organism within the textile structure and its morphological potential.

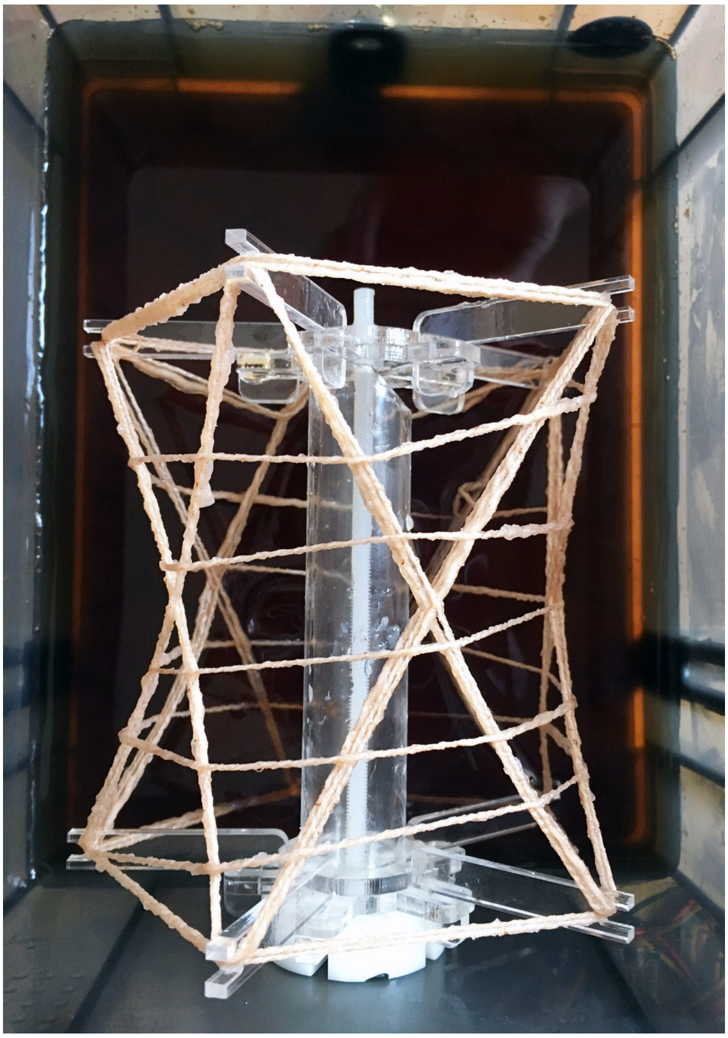


Figure 142 . Setup 2, test 2 in rotary incubator before incubation

→

Figure 143 Specimen after incubation (10 days)

Figure 144 . Detail BC morphology 1

Figure 146 Detail BC morphology 3

Figure 145 . Detail BC morphology 2

Figure 147 Detail BC morphology 4

6.2.3. Etude 3: *Sporosarcina Pasteurii*

The following étude investigates the ability of the bacterium *Sporosarcina pasteurii* to precipitate calcite on a textile medium as a structurally enforcing matrix.

Context

Microbiologically induced calcite precipitation, or biocalcification, is a naturally occurring process. It can be found in soils across the world, as well as in microbial mats both at sea and on land. These microbial mats are considered to be an integral part of the earth's oldest ecosystems (Dupraz et al. 2009). The majority of the earth crust's calcite can be accounted for by microbial activity and its by-products (Al-Salloum et al. 2017). Microbial communities, as found in maritime Stromatolites, consist of complex and interdependent microbial mats (Figure 148). They generate their own habitat by successively forming calcite-based structures, providing a highly resilient habitat and protection enabling a variety of different organisms to thrive. The resulting structures form through microbially induced mineralisation, a sub-type of biologically induced mineralisation. This process describes a process of material formation derived from the direct interaction between an active microbial culture and its immediate environment (Dupraz et al. 2009). In the case of Stromatolites, their complex morphogenesis involves inorganic particles (such as sand) being "soldered" together by sticky microbial mats, as well as calcifying bacteria, while being shaped by hydrodynamic conditions of the specific habitat and the resulting constant abrasion and deposition of material. Through this process a highly resistant multi-layered, living bio-composite material emerges, which can endure over geological periods (Bosak et al. 2013).[19]

It is important to note that the process described here is inherently different to biologically controlled mineralisation which occurs, for example, in molluscs or mammals to form external or internal skeletal structures. In this case, cellular activity directly steers the growth morphology and location of the mineral formation (Lowenstam & Weiner 1989; Dupraz et al. 2009). A significant difference, therefore, is that biologically induced mineralisation is dependent on the immediate environment in which it takes place in (for the supply of reactive chemicals), whereas biologically controlled mineralisation can happen independently from environmental factors (De Muynck et al. 2010).

19 Some stromatolites of the Archean and Proterozoic age grew many metres in diameter and height, spreading over hundreds of square kilometres (Bosak et al. 2013; Truswell & Eriksson 1972)

Figure 148 Stromatolites in Bacalar, Mexico

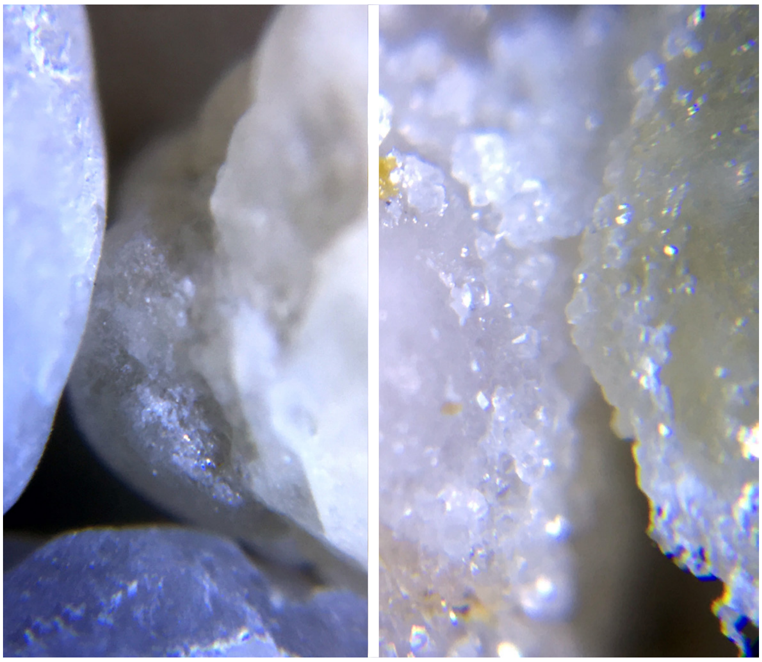


Figure 149 Untreated sample (left); Bio-calcified sample (right)

Numerous bacteria strains have been observed to induce microbial mineralisation processes. They can be categorised into six main categories according to the way they precipitate carbonate through distinct metabolic pathways (photosynthesis, ureolysis, denitrification, ammonification, sulphate reduction and methane oxidation) (Zhu & Dittrich 2016). *Sporosarcina pasteurii* (*S. pasteurii*), a ureolytic bacterium naturally propagating in soil, is well adapted to changes in pH, temperature and different moisture levels (Al-Salloum et al. 2017). Its resilience and tolerance towards changes in its environment makes it the favoured choice for biotechnical calcification applications.

S. pasteurii triggers a complex reaction by enzymatically breaking down urea, resulting in ammonia and carbamic acid, which is then hydrolysed to ammonia and carbonic acid. Ammonia then turns into ammonium and hydroxide ions while carbonic acid forms bicarbonate ions. The hydroxide ions increase the pH, affecting the bicarbonate equilibrium and generating carbonate ions. In the final stage, carbonate ions precipitate as calcite (Al-Salloum et al. 2017).

The generated calcite crystallises within a given granular medium, forming calcite links between adjacent grains (Figure 151). These links, just micrometres in size, build up a porous matrix while gradually solidifying the material and thus altering its global behaviour (Esnault Filet et al. 2012).

Naturally these processes occur in porous and/or granular materials such as sand or soil over decades (Stocks-Fischer et al. 1999). In laboratory settings these processes can be isolated and executed in optimal conditions, thus reducing the development timescale from years to a few days (Esnault Filet et al. 2012).

Recent studies and applications showed that microbiologically induced mineralisation processes can be used for various architectural applications, which range from the remediation of weathered limestone structures and monuments (Tiano et al. 1999; Perito & Mastromei 2003) and underground solidifications (Esnault Filet et al. 2016) to commercially available building materials in the form of bricks or cladding elements (eg. Biomason USA) (Ednie-Brown 2013, Bernardi et al. 2014).

Jonkers & Schlangen (2007) experimented with biomineralising bacteria as a self-healing agent within concrete structures (Figure 150). Alkali-resistant bacteria cultures were immobilised in a concrete matrix and dried for several days. After induced fracturing of the samples, followed by an incubation process, the experiment showed that it was possible to revive parts of the dormant bacteria and trigger bacterially induced calcite precipitation. The project aims to

Calcified concrete cracks

Quantification of crack-healing in novel bacteria-based self-healing concrete (Wiktor & Jonkers 2011), p. 765

(Image redacted for copyright reasons)

Figure 150 Calcifying bacteria as an agent for self-healing concrete (Wiktor & Jonkers 2011)

Calcite link between sand grains

Biocalcification of Sand through Ureolysis (Chou et al. 2011), p. 1186

(Image redacted for copyright reasons)

Figure 151 Sand grain adhesion through bacterially generated calcite bridge (Chou et al. 2011) incorporate dormant bacteria during the manufacturing process to autogenously repair minor fractures in concrete surfaces as a result of water ingress (Wiktor & Jonkers 2011).

As well as the investigations into product development or solely technical applications, the technology also prompted various speculative architectural projects. Working with a living entity which can be understood as a co-designing agent within the construction process is a fairly recent concept within architectural manufacturing (Armstrong 2014). Therefore it is a very attractive topic for architects and students of architecture to engage with. Speculative projects draw upon the underlying principles and systems of the process and try to frame them within an architectural design context.

Larsson (2010), for example, proposed to use the technology to build a megastructure made entirely from bio-calcified sand, as a countermeasure against desertification in the Sahara region. The design imagines a inhabitable 6000km-long megastructure constructed with a process of in-situ bacterial injections into the desert sand. By injecting the bacteria in a controlled, predetermined pattern, using a method similar to the one investigated (and commercially developed) by Filet et al. (2016), Larsson's design envisions a localised solidification within the sand mass. The injection system is designed to partially solidify the structure, leaving unsolidified zones which can be excavated after the treatment, thus generating inhabitable cavities (Figure 152).

Hein (2014) focused on morphological and structural granular aggregation triggered by the unconventional treatment and solidification method (Figure 153). The observations on small-scale experiments, which look into material aggregation as well as fluid dynamics, an integral part of the solidification process, are abstracted into a computational model which then drives the final design process.

The bacterially generated material is comparable to conventional natural limestone in its appearance as well as its performance (Bernardi et al. 2014); however, biotechnology enables direct interaction with its creation, which under natural conditions would take years. This technological opportunity opens up new possibilities for architecture.

The projects discussed above illustrate in an exciting way that it is not only the bacterially generated material that can be of interest for the design process, but also the process of the treatment as such. Engaging with the process of material generation whilst applying design tools and methodologies derived from architectural design (such as CAD/CAM processes) maximises the scope of architectural design and the field of biology, while triggering new streams of research on both sides.

Dune solidification scenario illustration

https://www.designboom.com/architecture/magnus-larsson-sculpts-the-saharan-desert-with-bacteria/

(Image redacted for copyright reasons)

Figure 152 Speculative process for local dune solidification through injection of bacterial solution (Larsson 2010)

Sand solidification scenario illustration

https://issuu.com/anjahein/docs/microbial_morphologies, p.69

(Image redacted for copyright reasons)

Figure 153 Flow rates as design parameter for structural morphology (Hein 2014)

As well as suggesting new opportunities for design, the materials that are generated also offer a more environmentally sustainable material for architectural purposes. With the building sector significantly consuming around 30 per cent of global energy and contributing concomitantly to global emissions (UNEP 2016), it is crucial to find suitable and more sustainable alternatives. Bio-cementation (or microbiologically induced calcite precipitation) can be seen as a sustainable alternative to methods using conventional construction materials such as cement and concrete, as it does not involve the very energy-intensive sintering processes necessary to produce cement-based materials (which accounts for to up to 7 per cent percent of anthropogenic CO2 emissions) (Jonkers et al. 2010; Achal & Mukherjee 2015).

The architectural applications of the process, however, focus mainly on the solidification of inorganic granular materials such as sand, gravel, polyurethane or glass beads (Bang et al. 2010). The use of granular materials imitates the bacterium's natural habitats, which are mainly soil and sand-based environments. The majority of research in this field is undertaken to improve the compressive strengths of treated materials or optimise the process, or for remediation purposes. The distinct brittleness of the resulting materials can be accounted for by the similar properties of the individual constituents, with granular mineral materials such as sand being embedded in a biologically derived calcite matrix (Bernardi et al. 2014). Although the resulting material can be understood as a composite material, the similitude of the matrix (in this case calcite) and the discontinuous phase (sand) lacks the synergetic effect which is achieved by incorporating a fibrous reinforcement.

Fibrous additives add another functional layer to the material, improving tensile stress performance. Wen et al. (2018) successfully tested a mixture of randomly distributed polypropylene fibres and linear bamboo strips and a quartz sand mixture, which resulted in an increase in the material's peak strength after bacterial treatment by up to 34 per cent (Figure 154).

Choi et al. (2016) used PVA fibres in a similar experimental setting, claiming an increase of 138 per cent in compressive strength and an 186 per cent increase in the tensile stress performance, while minimising the brittleness by 50 per cent. These figures clearly show that a fibrous additive conclusively improves the material's performance. These experiments generate a composite system consisting of three layers of different materials – sand, fibres and microbial calcite (Figure 155).

Another approach is described by Hao et al. (2018), who deployed a microbial calcite layer on the surface of polypropylene (PP) fibres in order to increase the bonding performance between the cementitious matrices and fibre reinforcement. The two-step process starts with a

Material testing fibre reinforced bacterially solidified brick

Experimental investigation of flexure resistance performance of bio-beams reinforced with discrete randomly distributed fiber and bamboo (Wen et al. 2018), p. 249 fig.7

(Image redacted for copyright reasons)

Figure 154 Fibre-reinforced, bio-calcified sand brick (Wen et al. 2018)

SEM microscopy fibre reinforced bacterially solidified brick

Experimental investigation of flexure resistance performance of bio-beams reinforced with discrete randomly distributed fiber and bamboo (Wen et al. 2018), p. 248 fig.11

(Image redacted for copyright reasons)

Figure 155 Electron scanning microscopy: fibre interaction with substrate and calcite (Wen et al. 2018) microbiological treatment of PP fibres (*S. pasteurii*) which are then, after the calcite deposition on the fibres, mixed with concrete. The experiment resulted in a doubling of the material's resistance to cracking and its energy absorption capacity (Hao et al. 2018).

In this case, the material system again consists of three materials, the PP fibres and a microbial calcite layer embedded in a cementitious matrix. These experiments did not investigate the potential of the microbial calcite matrix itself as a binding agent within a fibrous composite, generating a bacterially driven as well as sustainable solidification process. The following hypotheses were conceptualised as a departure point for further investigation of the complex relationship between the fibrous medium and the living organism. The aim is to design a basic system and treatment methods to open up future scenarios which could incorporate properties such as autogenous self-repair (De Belie et al. 2018).

Hypotheses

Based on the projects reviewed in the previous chapter, it became apparent that the prevailing research in the field of bio-calcification does not sufficiently consider fibrous materials as a potential medium for the process. The following hypotheses aimed to assess the potential of a *S. pasteurii*-based textile microbiome.

1. A fibrous medium presents a suitable environment for *Sporosarcina pasteurii* to actively precipitate calcite.

2. The bacterially generated calcite matrix is able to alter the global behaviour of a textile structure.

The investigations were conducted using the Biocalcis protocol (Esnault Filet et al. 2012) with the collaborative support of Soletanche Bachy France in their laboratories.

Setup 1 (Figure 156) explored the bio-calcification of a knitted, sand-filled tube with the Biocalcis protocol.It is an initial exploration to introduce a textile component into a setup developed for treating columns of granular material. By doing this the established protocol for the Biocalcis treatment can also be applied, as the necessary lab equipment can be used without being changed, thus speeding up the initial testing and contributing to familiarisation with the process and its potential and limitations. In anticipation of the planned collaboration with fellow ArcInTex Early Stage Researcher Daniel Suarez (UdK Berlin), whose research concerns scaled-up knitting patterns as structural elements, the material sample of Setup 1 had already aimed to explore the distinct morphology of knitted patterns.

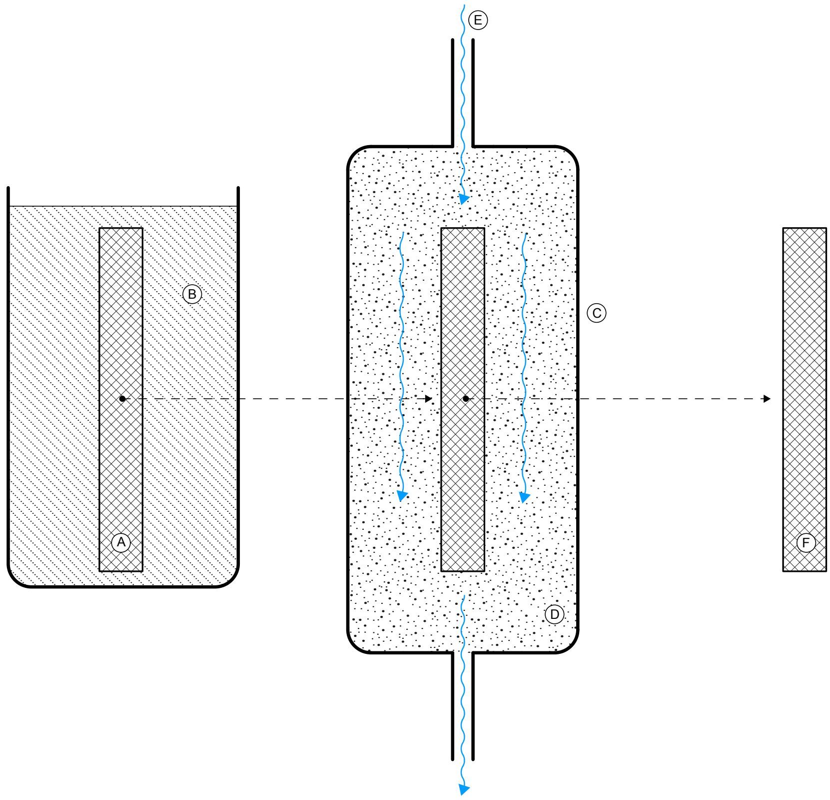


Figure 156 Setup 1

Figure 157 Innoculated Substrate

Figure 158 Untreated sand filling

Protocol

The three-step process (Figure 156) starts by submerging a sand-filled knitted tube (cotton) as well as a bulky yarn (synthetic sleeve and filling) (A) in a bacterial solution (water, NaCl, *Sporosarcina pasteurii*) (B) for approximately 20 minutes for the bacteria to fully permeate the samples and adhere to the fibres and sand grains. In the second step the sample is removed from the solution and hand-knitted to form a tubular structure. It is then placed in an enclosed container (200mm high and 68mm long and deep) (C) with neutral sand (no bacteria) (D), which holds the sample in place by acting as a support structure.

The container is then sealed at the top and bottom with silicone and the calcification-triggering liquid (consisting of water, calcium chloride ($CaCl2$, VWR Chemicals) and urea ($CO(NH2)2$,VWR Chemicals)) is injected in the inlet (E). The liquid permeates the whole substrate in the container while only triggering calcification in the (bacterially active) sample. Four injections of calcifying liquid were undertaken (400ml, flow-rate 40ml/min) for two days.

Results

After the treatment the container was opened and the sand column could be extracted. The neutral sand could easily be removed, whereas the sand-filled knitted tube was solidified (Figure 159). The second sample, made from synthetic fibre, did not solidify, suggesting that the process is more likely to work with natural fibres.

Figure 159 Setup 1 result, solidified treated substrate, untreated support sand removed

Setup 2:

Setup 2 (Figure 160) applies a *S. pasteurii*-based textile microbiome on different fibre types to determine the correlation between the fibre and the textile microbiome during the calcification process.

Objective

In order to determine whether the bacteria would adhere to the fibres, thus enabling it to form calcite within the media, a series of tests were conducted with different (off-the-shelf) yarns made from natural fibres. Natural fibres were purposely chosen to generate a homogeneously bio-derived sustainable material. Within this material class the selection was further narrowed down to abundant, low-cost and available materials in anticipation of a larger-scale proof of concept.

Setup

A : yarn

B: 1. Step: bacterial solution

2. Step: calcifying solution

C: beaker

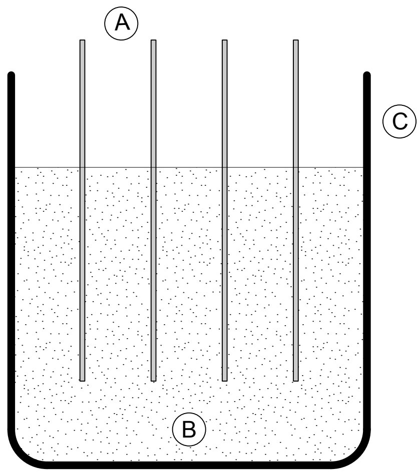


Figure 160 Setup 2

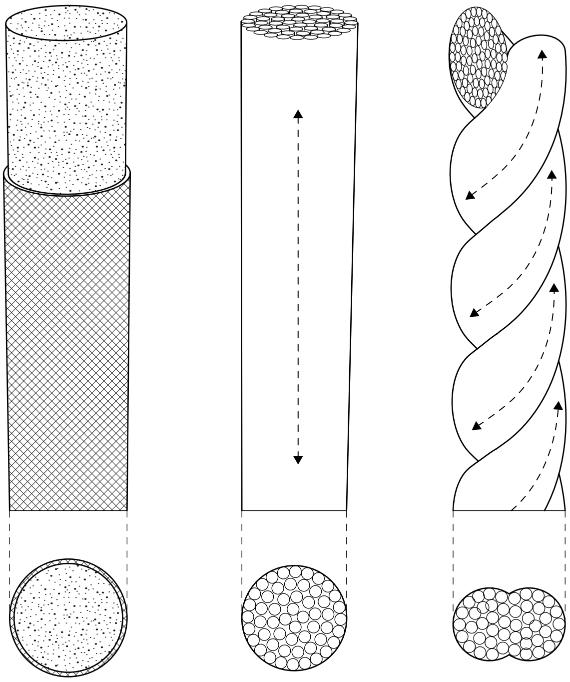


Figure 161 Sample construction, internal geometry and materi-ality

Figure 162 Setup before submersion

Figure 163 Active sample (bacteria) in calcifying liquid; visible calcite precipitation on the surface

Sample preparation

The yarns were treated as individual strands as well as in configurations, as follows:

1. Knitted tube with sand core (approx.10mm / approx. 6.5mm) (Figure 161 , left)

2. Linear array with metal sleeve (approx. 20mm) (Figure 161 , middle)

3. Multi-strand twist (approx. 10mm) (Figure 161 , right)

Protocol:

The different yarn samples (were three-quarters submerged in an active *Sporosarcina pasteurii* culture solution for approximately half an hour in order for the bacteria to adhere to the fibres. In the second step the solution was then exchanged for the calcifying solution (consisting of water, calcium chloride (CaCl2, VWR Chemicals) and Urea (CO(NH2),VWR Chemicals)) in order to trigger the calcifying process (Figure 163). For this setup the treatment cycle was repeated four times, with a final phase of rinsing with water followed by drying at an ambient temperature.

Results

The samples underwent a qualitative and quantitative examination through visual examination as well as testing for compressive and tensile load cases. All the samples showed clear signs of microbiologically induced calcification in the form of white calcite crystals deposited on the surface of the samples (Figure 164). This was further affirmed by the microscopic observations (Figure 165) conducted after the process, which clearly indicate an effective coating of the fibres with microbial calcite on the fibre level. The sectioning of the larger samples showed that the calcite matrix spread homogeneously across the diameter of the composite (Sample 4,5,6, Figure 164, right). Upon visual inspection, the individual yarns (Sample 1,2,3, Figure 164 , left) were covered homogeneously with microbial calcite.

However, the untreated jute yarn, due to its very coarse, irregular finish, appeared to generate a large surface area, thus presenting increased space for the bacteria (*S. pasteurii*) to adhere to. At the same time its coarse finish promoted the cross-linking of multiple strands of yarn by the overlapping and entangling of the individual yarns. After the treatment these cross-links contribute to the stability of the linkage between individual stands of yarn. This observation suggested that the calcite deposition is primarily promoted by an increased surface area: thus more from its geometry than from the material itself.

Figure 164 Treated samples; visible calcite deposition on the surface

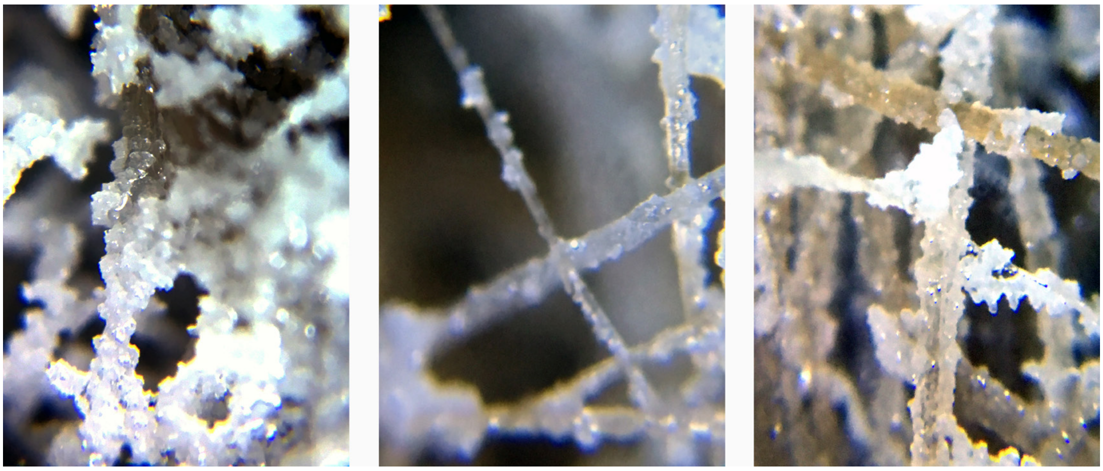


Figure 165 Calcite deposition on microscale; adhesion of individual fibres due to calcite links; 200X magnification

Structural testing

The testing involved compression testing of a 2cm longitudinal sample (Figure 166) extracted from the treated specimens, as well as tensile testing of a 5cm-long sample. Although, the structural testing was performed with precision machinery[20], the results should be seen as an indicator and proof of concept for the structural transformation of the material rather than a consistent data set, due to the lack of a comprehensive series of tests[21]. However, the tests allow for an initial estimate of, and comparison between, the different material compositions.

The samples performed well in the compression test, with all the specimens demonstrating improved vertical load resistance. Even though no tests with untreated materials were performed, it can be assumed that due to their composition, which consisted either of loosely bundled untreated jute fibres or knitted sleeves filled with uncompressed dry sand, their ability to withstand vertical loads would be comparatively poor.

20 The structural tests were conducted at the University of Westminster's material testing facility.

21 For a reliable data set, at least five samples of each material should be tested to establish a consistent profile of the structural characteristics and behaviour. Only a limited number of specimens could be tested, due to the low quantity of treated material available.

Figure 166 Extracted test specimens

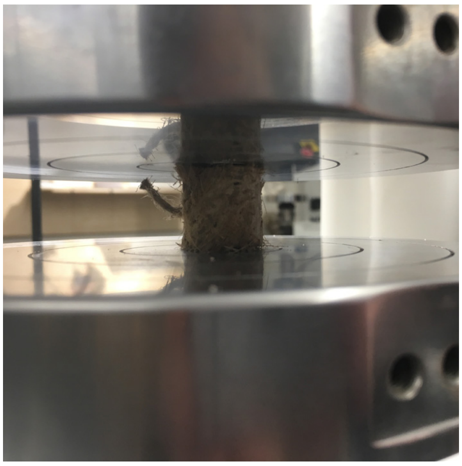


Figure 167 Compressive testing

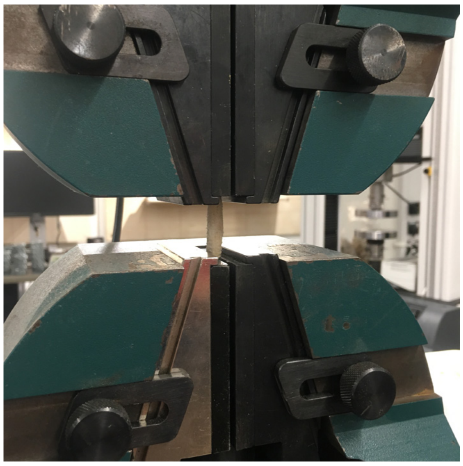
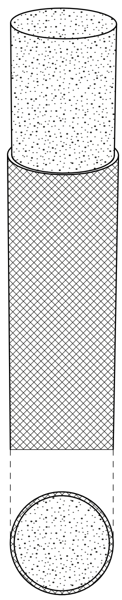
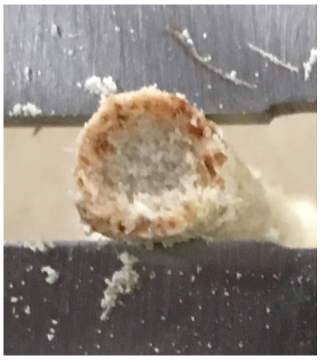


Figure 168 Tensile testing

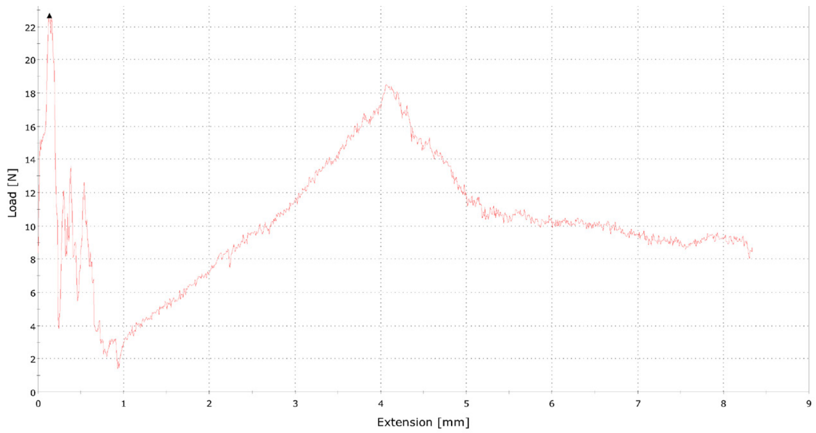
Test 1 and Test 2

These tests involved compression and tensile testing of a calcified sand-filled, knitted tube (Table 1, Table 2). According to the results of the compression tests, an increase in the surface area of 136.4 per cent (6.5 mm diameter = 0.33 cm2 to 10mm diameter = 0.78 cm2) resulted in a 1786.5 per cent increase in compression strength. This significant increase is rather unlikely, given the similar material composition of the two test specimens. The fluctuation could be the result of a non-homogeneous distribution of sand within the tube, which affected the structural integrity of Sample 1 at an early stage of the test, thus not accurately accounting for its strength.

As expected, the tensile test performed well due to the fibrous sleeve, which improved the sample's ability to withstand tensile forces, as the calcified sand by itself cannot withstand tensile forces very well, due to its brittle, crystalline structure.

TEST 1		
Data	Material composition	Test specimen
Diameter: 6.5 mm Test lenght: 20 mm Material: Sand core, knitted cotton sleeve	 0.33 cm^2 sand core knitted sleeve (cotton)	section / top view  side view 
Compression test		
max load capacity 22.5 N max load per cm^2 7.4 N		
Tensile test		
max load capacity 66 N may load per cm^2 21.8 N		

Compression test graph



Tensile test graph

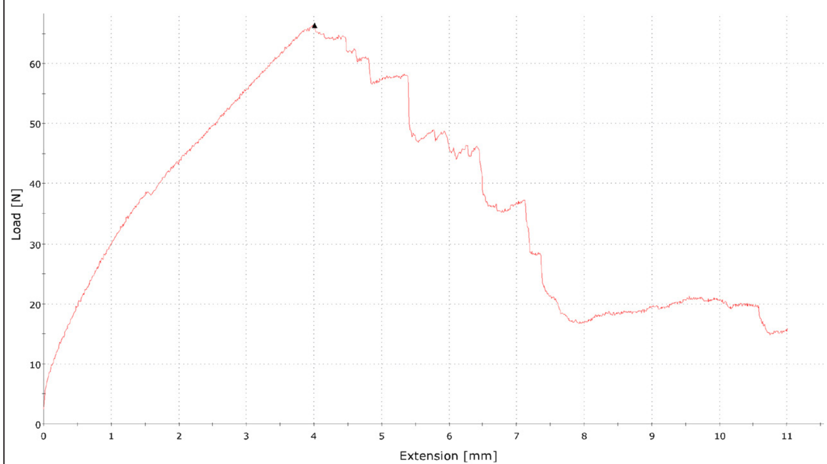
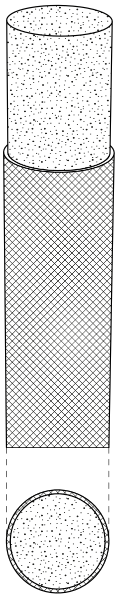
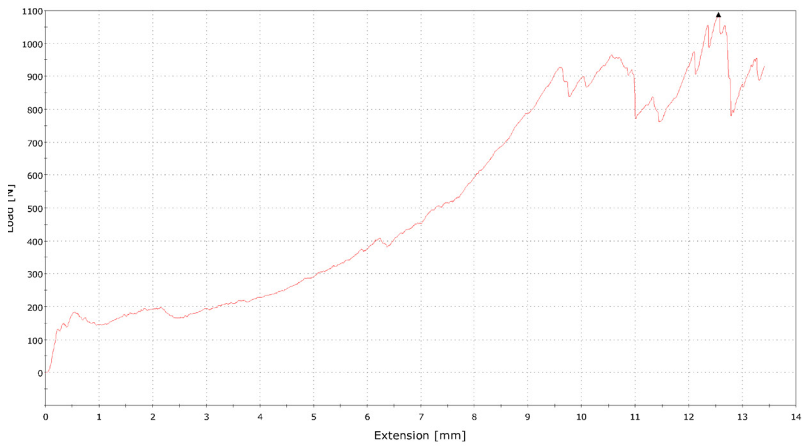


Table 1: Test 1 Biocalcifiaction

TEST 2		
Data	Material composition	Test specimen
Diameter: 10 mm Test lenght: 20 mm Material: Sand core, knitted cotton sleeve	 0.78 cm^2 sand core knitted sleeve (cotton)	section / top view  side view 
Compression test		
max load capacity 179 N max load per cm^2 139.6 N		
Tensile test		
max load capacity 137 N may load per cm^2 106.9 N		

Compression test graph



Tensile test graph

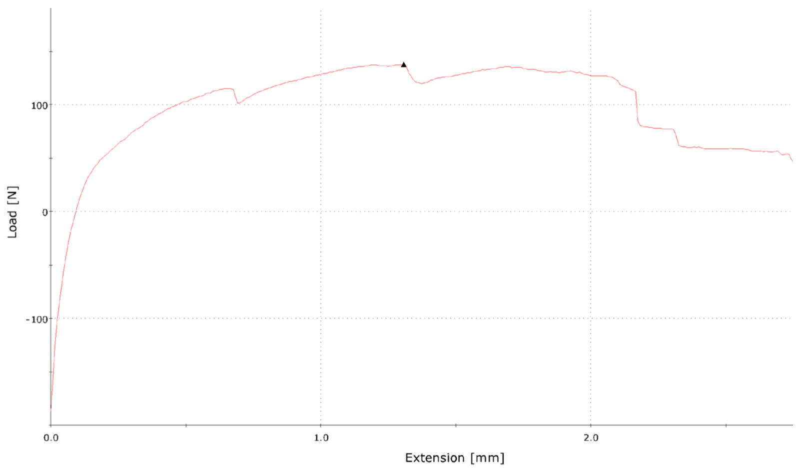


Table 2: Test 2 Biocalcifiaction

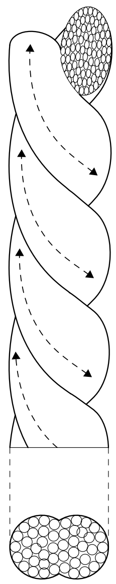
Tests 3 and 4

These tests consisted of testing two samples of calcified jute fibre in two different configurations, moving from sand as an additional substrate for S.pasteurii to a solely fibrous medium. The first sample consisted of of twisted jute fibre which was, again, entwined to form a rope-like cord (Table 3). This generated a rather dense structure which left less intermediate space within the individual threads for calcite to build up. However, a consistent calcification was achieved, which also spread homogeneously throughout the material. The compression test, however, showed that the twisted configuration generated weak points within the sample, as the fibres run diagonally to the direction of force.

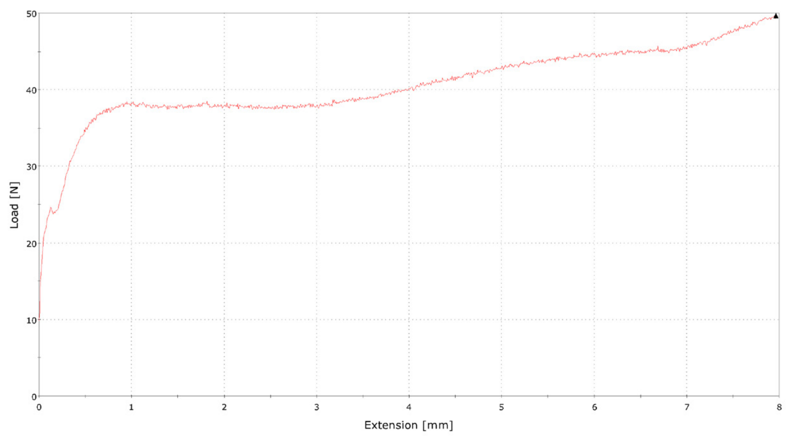
Test 4 investigated a directional fibre array, which was achieved by confining the individual fibres within a knitted sleeve made from stainless steel (Table 4). This way the individual threads maintained their direction as well as an overall linear shape during the treatment. This scaffolding was removed after treatment, so it did not influence the test results (Figure 169). In contrast to Sample 3, this array generated more intermediate space between the fibres because of its non-twisted, rather loose, linear alignment, which enabled more calcite to be deposited, which, it can be assumed, in addition to the directional array of the fibres, increased the vertical load capacity by 176.4 per cent (N/cm2).

Figure 169 Removal of stainless steel sleeve

TEST 3

Data	Material composition	Test specimen
Diameter: 9mm/11mm Test lenght: 20 mm Material: Jute twine bundeled and twisted	 0.81 cm^2 twisted fibre (arrow)	section / top view  side view 
Compression test		
max load capacity 37 N max load per cm^2 28.8 N		
Tensile test		
max load capacity 823 N may load per cm^2 666.6 N		

Compression test graph



Tensile test graph

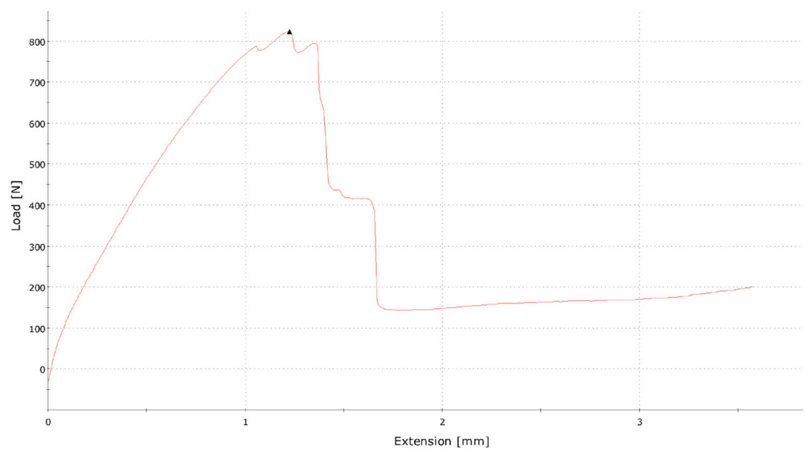
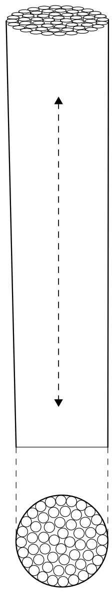
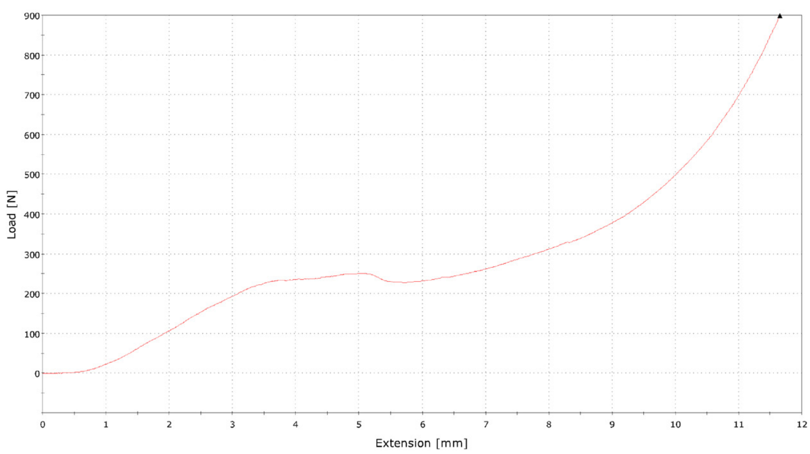


Table 3: Test 3 Biocalcifiaction

TEST 4

Data	Material composition	Test specimen
Diameter: 20 mm Test lenght: 20 mm Material: Jute twine bundeled	 3.14 cm^2 Jute twine bundeled	section / top view  side view 
Compression test		
max load capacity 250 N max load per cm^2 79.6 N		
Tensile test		
max load capacity 3291 N may load per cm^2 1048 N		

Compression test graph



Tensile test graph

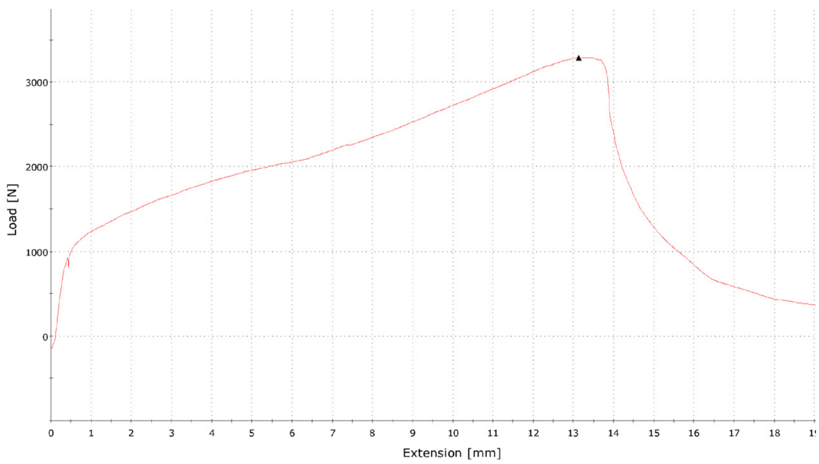


Table 4: Test 4 Biocalcifiaction

Discussion

Etude 3 showed that a textile microbiome based on the bacterium *S. pasteurii* actively interacts with and changes its fibrous substrate. Both hypotheses could be investigated through the two setups of étude 3, and the results delivered valuable insights for further improvement and future research trajectories.

Hypothesis 1:

1. A fibrous medium presents a suitable environment for *Sporosarcina pasteurii* to actively precipitate calcite.

Both setups demonstrate the development of a calcite microstructure on the selected substrates. The tests showed that *S. pasteurii* can be applied to a range of different natural fibres and textile structures, generating an active textile microbiome, and demonstrated its capability of precipitating calcite on/within the substrate. Specifically, the submersion of the samples, which differs from the original Biocalcis protocol, successfully generated a bacterially induced calcite matrix. Furthermore, the tests suggest that an efficient calcite deposition is more dependent on the distinct (micro) morphology and quality of the fibres than on the raw material they are derived from.

Hypothesis 2:

2. The bacterially generated calcite matrix is able to alter the global behaviour of a textile structure.

Etude 3 clearly indicates that the bacterial treatment of sand-filled tubular textiles, as well as the solely fibrous media, with *Sporosarcina pasteurii* results in the increased stability (compression) of the samples. The generated "coarse" data enabled a general assessment of the performance of the different investigations demonstrated in Etude 3. The test results of the sand-filled tubes, for example, indicated that granular filling, probably due to the manual filling method, tends to generate a non-homogeneous material, resulting in weak points which can lead to early failure (Test 1/2). Tests 3 and 4 showed that the solely fibrous setup was able to improve on the performance of Tests 1 and 2 (N/cm2). Setups 3 and 4 demonstrated that a linear fibre array performed better than a twisted fibre setup. The étude consistently proved that the bacteria culture was able to adhere to off-the-shelf jute fibres while generating a rigid composite, and is potentially suitable for a larger-scale application.

6.2.4. Etudes: Summary

The three études enabled an exploratory investigation of three different microorganisms and their behaviour on a textile substrate, with each forming a distinct and active textile microbiome. Every microbiome had different demands in relation to their environment, substrate and culturing, while displaying inherently different behaviour.

The most important environmental factors related to moisture content and temperature. Mycelium, for example, had to be kept at an ideal temperature of around 28-30°C to achieve optimal proliferation, whereas the activity of *S. pasteurii* could take place within a much wider spectrum of temperatures. This is also related to the inherently different biological processes taking place. The propagation of mycelium, which generates a fibrous, living hyphae network, is based on cell division, whereas the ureolysis of *S. pasteurii* is based on an enzymatic biochemical reaction. Thus the biological processes and the generated materials are inherently different. Mycelium is chitin-based and *S. Pasteurii* triggers calcite deposition.

Humidity, as another crucial environmental factor, also differs starkly for each organism. While the bacterial cellulose generation of *A. Xylinum* takes place naturally at the interface between liquid and air, mycelium prefers a substrate with a constant humidity. At the same time, the individual nutritional demands varied significantly. This is related to the specific demands of the microorganisms and their distinct metabolism and exchange with their environment.

The études illustrate some of the various modes of culturing and applying the specific organisms. In comparison to a conventional biologically derived material such as wood, the mode of fabrication is inherently different. Wood, for example, usually develops in its natural habitat and form over a relatively long time-span, as a tree. The tree is harvested and its wood post-processed for its final application. These two factors, time and processing, which are also significant economic factors, are approached differently in the context of the études. For the tree to develop a specific shape it needs to develop a self-supporting structure. This process, driven by photosynthesis, takes years to happen. Once harvested, the wood needs to be shaped and manipulated to fit a specific purpose, which demands a process which is simultaneously energy intensive and inefficient in terms of the mode of consumption of the raw material. An organic, mostly circular, branching shape is usually transformed into orthogonal segments to fit construction standards, which results in extensive waste offcuts.[22]

22 Although these offcuts are “recycled”, or used for energy production, these waste materials cannot be exploited for their full performative potential.

The textile microbiome thus offers the potential to support the generation of a natural material. While the shape is determined by the textile scaffold, a matrix material gradually builds up, solidifying the structure through the use of biological processes. As the material has already been incubated in its anticipated shape, further post-processing and shaping is not necessary.

As outlined in the section *fibrous structural strategy* (tree), the scaffold presents a base structure which enables the fast development of bio-derived matter. Rather than a gradual build-up of material through the expansion of its outer perimeters, as in the example of a tree, a simultaneous build-up alongside and throughout the textile scaffold can occur. *Acetobacter Xylinum* is able to generate bacterial cellulose through its distinctive metabolism. Cellulose is, besides lignin, one of the main constituents of wood, and therefore presents a suitable organism to potentially grow a wood-like material in a laboratory setting. This could offer the possibility of monitoring and controlling quality, reducing offcuts while saving resources and time. While cultivating wood-like materials in a laboratory setting might initially seem counter-intuitive, the pressing environmental challenges accelerated by extensive deforestation[23] call for unconventional and innovative solutions to transform the current unsustainable trajectory of fabrication.

The études enabled the investigation of the concept of an active textile microbiome and interdependent processes and materials while presenting a foundation for speculation and further development. All three études demonstrate an active textile micro-organism reacting to environmental stimuli by generating a distinct material (sub)layer, thus creating a multi-hierarchical textile-based composite through their specific metabolism.

23 According Prof. Wangari Maathai, Nobel Peace Prize Laureate 2004, deforestation accounts for approx. 20% of global carbon emissions which is greater than all transport systems combined (Dow & Downing 2016).

6.3. Column

A column is both a fundamental structural element and an archetypal constituent of architecture. Throughout architectural history this element has undergone constant reiteration according to prevailing architectural styles, material culture or technical and structural possibilities.

The scenario reimagined this fundamental architectural element in the light of contemporary materiality by harnessing the synergies of digital design, textile logic and biotechnology.

The intentional shift in terminology from a biological system (a tree) to an architectural element was undertaken to identify the translation process with a different domain. While the material system both incorporates and is inspired by biological systems, it remains an assemblage of analogies and strategies deducted from a biological system, but does not, however, resemble it.

The project intends to touch upon these principles, discussed earlier [24] :

1. Metabolism
2. Global geometry and topology
3. Structural gradient on a micro scale
4. Fibrous structural strategy

The following chapter outlines the multiple facets of the project , from engineering a new treatment method, material development and the knitting process, to the finished structure.[25]

24 See chapter 4, tree

25 The project emerged through a collaboration between Daniel Suarez and Soletanche Bachy (see Appendix I)

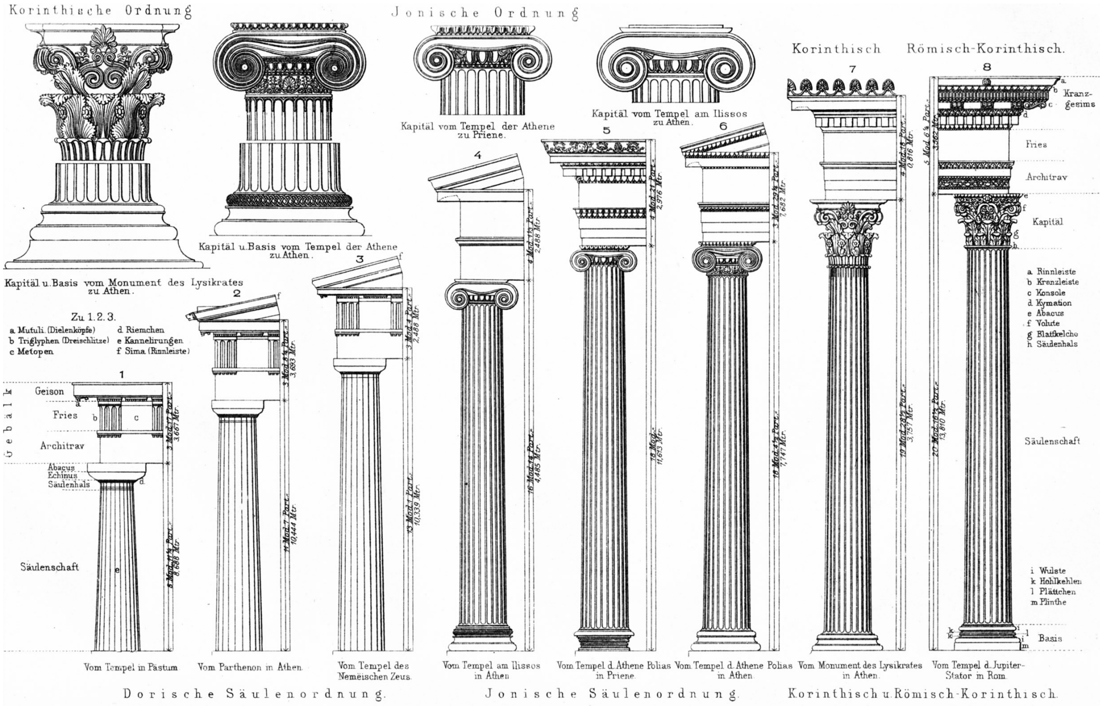


Figure 170 Orders of columns

6.3.1. Prestudies

Treatment strategy

Etude 3 showed that the solely fibrous samples that were tested present a suitable substrate for biocalcification. Simultaneously, the mechanical testing results demonstrated the structural potential for an increase in scale. The applied treatment process in étude 3, however, consisted of a full submersion of the specimens, which could not be realised for the anticipated size of the textile structure (h=160cm d=35cm), due to the increased amount of (bacterial and calcifying) liquid needed. This called for a more efficient treatment system. Inspired by agricultural irrigation systems, a strategy was conceived which consisted of continuously spraying the sample instead of fully submerging it. This system reduces the amount of liquid required while increasing the potential area of treatment.

Irrigation test setup

The setup (Figure 171) consists of a rotating container (C) driven by a stepper motor (D). The specimen to be treated (A, red) is suspended from the top of the container, thus simultaneously rotating. A second, static container (G), is positioned underneath the first container (C) and contains the bacterial and calcifying solutions as required. A static perforated tube (B) is mounted in the intermediate space between container (C) and specimen

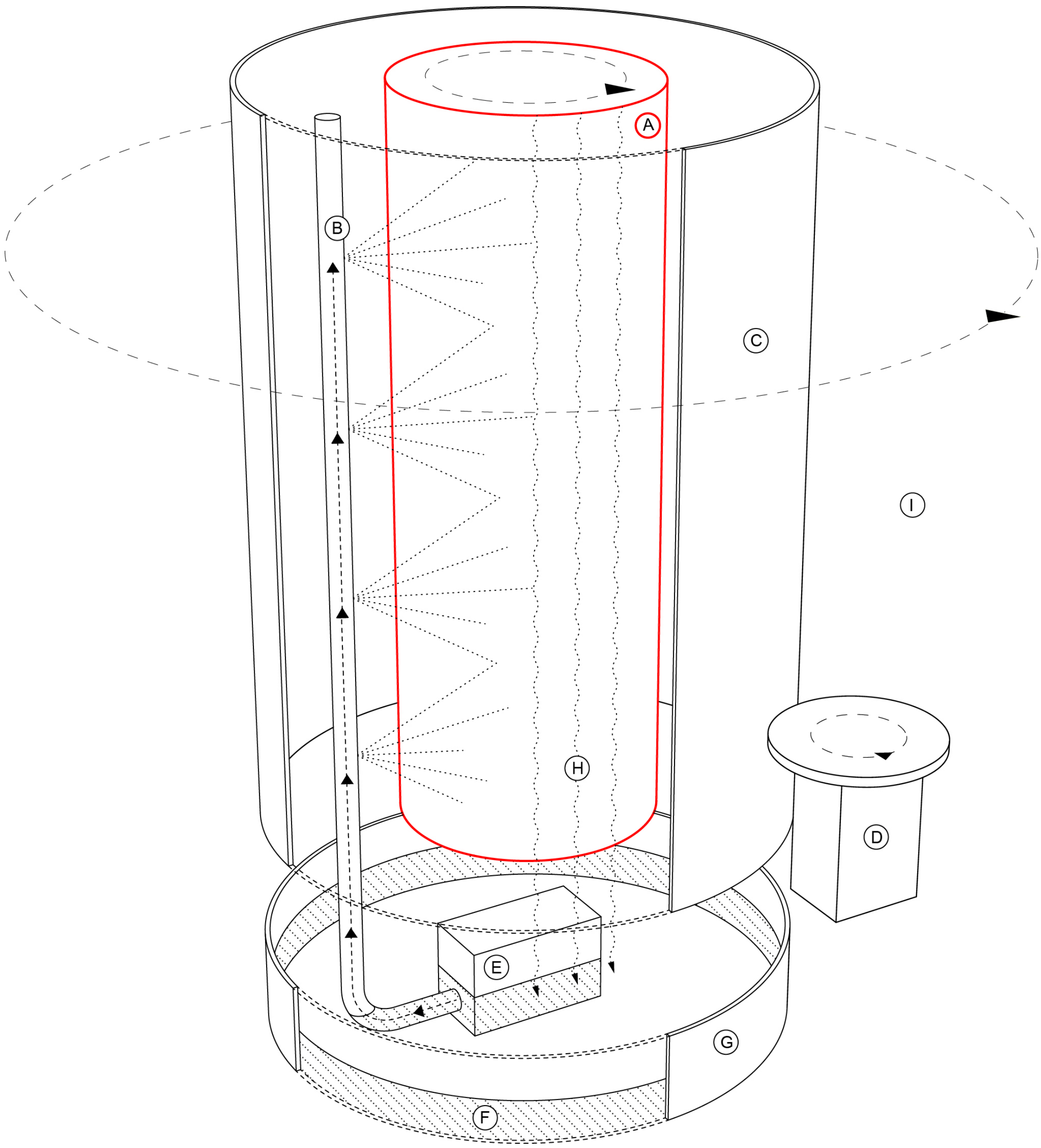


Figure 171 Test setup scheme

(H). The pump (E) is connected to the tube which, due to its perforation, disperses the liquid onto the rotating specimen.

Container 1 acts to shield off the residual spray from the process. The abundant liquid, once the sample is permeated, is able to drip off while being reused for another cycle. By applying this process, the amount of liquid could be significantly reduced, thus making the process more efficient as well as deployable on a larger scale.

Test sample preparation

The base material for the experiment consisted of a knitted tube which was filled with sand (0.2-2mm grain size), similar to Samples 1 and 2 in Etude 3. After preparation, the tube was hand-knitted in a single jersey pattern using a custom loom (Figure 172). The soft structure (Figure 173) was then mounted onto Container 1.

Process

The setup (Figure 174) was activated and the bacterial solution introduced. A total of two treatment cycles over the course of two days were undertaken. One cycle consisted of spraying the sample for 15 minutes with bacterial solution while it was rotating within Container (C) (Figure 171). After the spraying a one-hour break allowed the bacteria to fully permeate and adhere to the sample before changing the liquid from a bacterial solution to a calcifying solution, which was applied using the same system. The calcifying solution was subsequently sprayed on the specimen for approximately 30 minutes (Figure 175). In order for the bacteria to fully react within the substrate, a 24-hour break, in which the sample remained in container (C), was required. The process was repeated on the second day.

Figure 172 Knitting process, loom setup

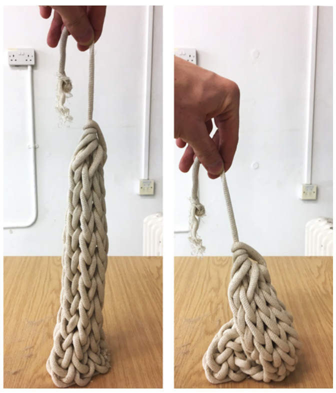


Figure 173 finished soft structure; not self-supporting

Figure 174 Test process

Results

1. Irrigation treatment

Following the treatment, the sample showed clear signs of bacterially induced calcification, which spread throughout the sample. However, no structural testing was undertaken at this point: the visual and haptic assessment delivered sufficient proof of the system's functionality (Figure 176).

2. Sample

The chosen geometry, a single jersey pattern, responded well to the treatment. The points of contact in the area around the individual loops maintained their adhesion after drying. Simultaneously, a global solidification of the structure occurred through the bacterial calcite deposition, resulting in a rigid structure.

Discussion

The successful test of the novel treatment system, as well as the transformation of the specimen, opened up the possibility for further up-scaling.

Although the process was able to deliver the anticipated outcome, the increased complexity of the setup resulted in several interruptions to the process due to technical difficulties. The issues were partly caused by the motor (Figure 171 , D) not being able to generate sufficient drag for the rotation of the container and thus the specimen. This problem was overcome by an adjustment of the motor and its speed. The second critical point concerned the liquid management. The gap between Containers C and G generated a leak, which had to be repeatedly sealed. Although these technical shortcomings caused several interruptions and had to be repaired throughout the tests, they generated valuable insights for the next iteration of the setup. Another key finding of the test was related to the applicability of the process in non-sterile environments. Although the test was executed within a laboratory, no specific sterilisation measures were in place during the process, and the results were not compromised by this fact. This suggests that an on-site application within a non-sterile environment is feasible. This finding impacts on the efficiency of the process significantly, as in this case there is no need for additional spatial separation or time- and resource-consuming precautions for sterile working.

No further experiments could be executed using a solely fibrous setup, due to laboratory time restrictions. The results of étude 3, however, suggest that an implementation of a solely fibrous medium is possible and, according to the structural testing results, even offer an increase in the structural potential of the material.

Figure 175 Irrigation process

Figure 176 Bio-calcified specimen

6.3.2. Large scale setup

The setup of the case study consisted of three main modules, the base structure, the loom and the bioreactor. The following section discusses each module in relation to its design, functionality and construction.

Objectives

The setup investigated a knitted structure similar to the one tested in the irrigation test setup, but increased its scale as well as its complexity in terms of the knitting patterns. The premise was to generate a knitted textile structure (approx. 160 cm in height and 35 cm in diameter) which could be pre-tensed prior to treatment using a substructure. During the treatment the structure was gradually transformed through bacterial calcification triggered by an *S. pasteurii*-based textile microbiome, inverting the load case from a tensile structural system to a compressive system (after removing the pre-tensing scaffold).

The study employs two geometric optimisation strategies (inspired by the tree analogy). The first strategy incorporates a material gradient. The planned knitting technique demands one continuous textile material for its manufacture. This distinct attribute of textile manufacturing offers the opportunity of applying variable thicknesses throughout the continuous substrate, which results in material savings as well as structural improvement. In the following case a gradual decrease in material thickness throughout the thread of the substrate over a length of 450 metres was applied. The material gradient resulted in an increased material deposition in the lower part of the structure to account for the increased structural demands of the base. Simultaneously, a reduction in material was achieved in the upper section, reducing the weight of the structure as well as the compressive loads for the base section. By applying the material gradient, the overall material consumption could be reduced by 28.8 per cent.

The second geometric optimisation strategy involved varying the knitting patterns throughout the textile structure. Each pattern displays a specific structural behaviour under different load-cases, which is accounted for by its unique geometry. Their geometry and behaviour are defined by loop length and tension, as well as by direction and global geometry (Duhovic & Bhattacharyya 2011). Through a targeted distribution of specific patterns, local densities, as well as openings, can be incorporated within a knitted system. This strategy consequently influences its structural behaviour and overall material consumption. The case study employed three different knitting patterns throughout four horizontal sections while maintaining a continuous manufacturing method. The pattern change was introduced by varying the knitting technique after each finished section without interrupting the continuous manufacturing – by cutting the material to length, for example.

In the following project, the manufacturing setup is not meant as a mere tool to generate a structure but should be understood as an integral part of a material system. Therefore, the idea of an installation, with its individual architectural presence, that would serve both as a knitting work-station that enabled the manual interaction and fabrication of the textile structure, and a bioreactor for the treatment, was conceptualised. The proposed installation is understood as a stage for a multi-actor fabrication process, facilitating the co-creation of an architectural structure by means of human dexterity, digital tools and microbial activity.

Components

1. Base structure

The tripod structure, which consists of CNC-milled and painted plywood modules, is the load-bearing element of the installation. Each of the three legs consists of three layers of 12mm plywood, connected by four wooden brackets and cross-braced with tensile metal wire thread, generating a structurally sound construction (Figure 178). The free space in the centre of the construction can accommodate a knitting loom (B) or a bioreactor setup (C) (Figure 177) held by six connection nodes, three in the lower part and three at the top, attached to the legs of the structure. The modular construction system ensures effortless transport and a time-saving setup, while the exchangeable working modules enable a streamlined and efficient process.

The base structure actively contributes to the process as a crucial element, providing the basic infrastructure for the project as well as conceptually staging the whole process. Therefore it intentionally plays an active role within the design language of the installation.

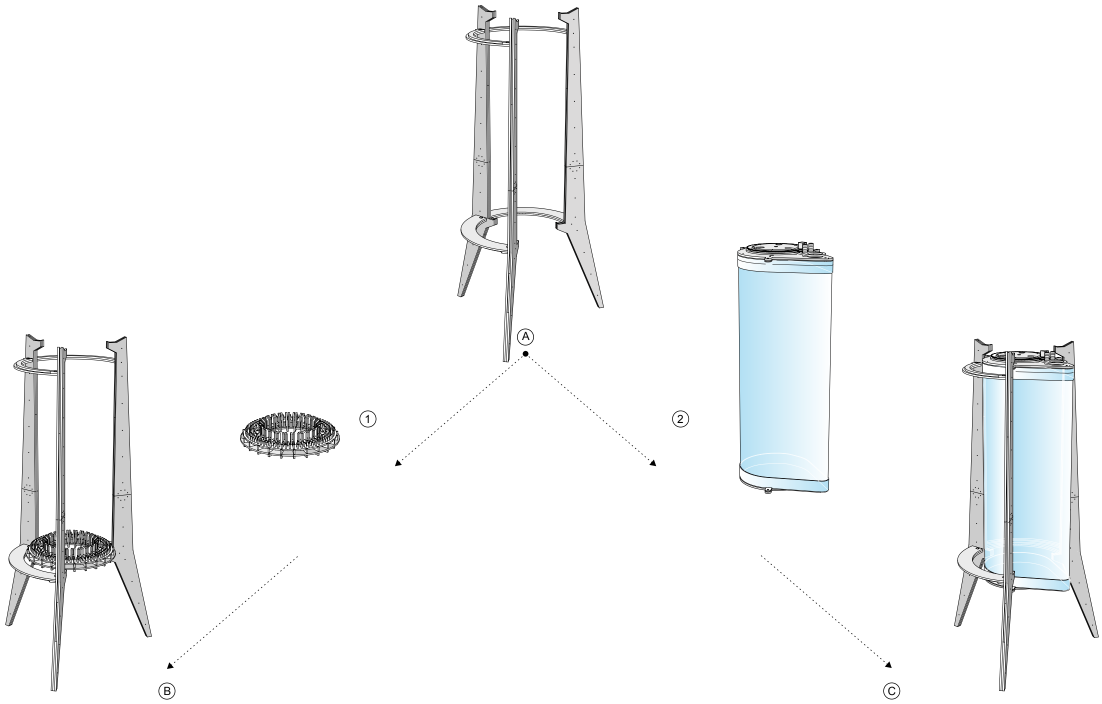


Figure 177 Modular concept
A: tripod base-structre;
B: knitting loom setup;
C: bioreactor setup;

structural system

A axonometry
B explosion
C front
D top

1 vertical loadbearing structure
2 horizontal connectors
3 cross bracing

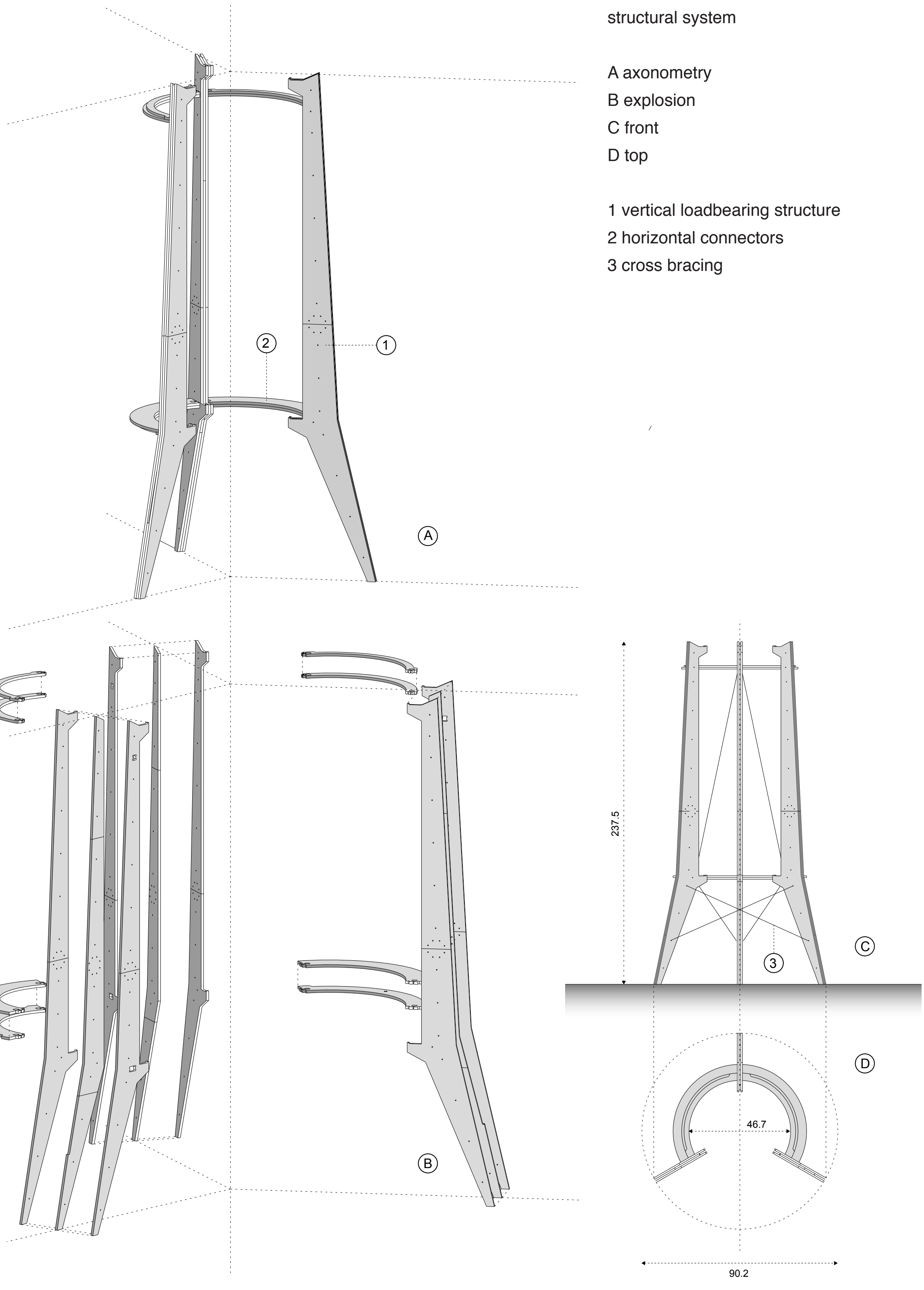


Figure 178 Base structure construction details and dimensions

2. Loom

The customised circular hand-knitting loom (Figure 179, Figure 180) consists of a base structure which can hold up to 48 pegs with an inner diameter of around 370 mm. It is constructed from CNC-milled, as well as laser-cut, plywood parts. The loom underwent several iterations during the preparations in order to streamline the labour-intensive hand-knitting process in the most efficient and ergonomic way.

In contrast to conventional looms, which by comparison incorporate small pegs in the millimetre range, the material specifications of the project demanded a complete re-design. Although conventional hand-knitting looms offered a blueprint, the use of a non-stretchable knitting material posed several challenges for the final peg design. Knitting is based on the physical manipulation of a continuous thread which involves the generation of intersecting loops. The process of “looping” is usually facilitated by the distinct “stretch-ability” of the material. In the case study, the selected material only possesses a marginal stretch factor. Therefore the pegs are designed to compensate for this missing characteristic through geometric optimisation. A thick base defines the loop length while a thin top provides space for free movement for the knitting process.

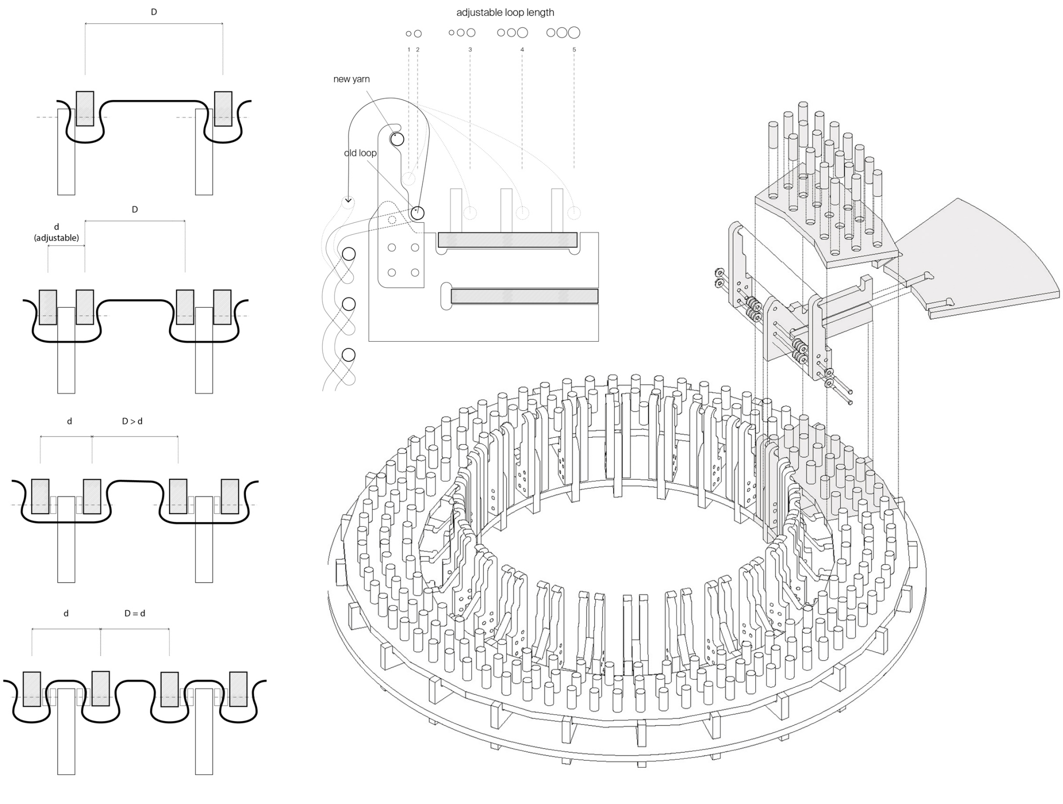
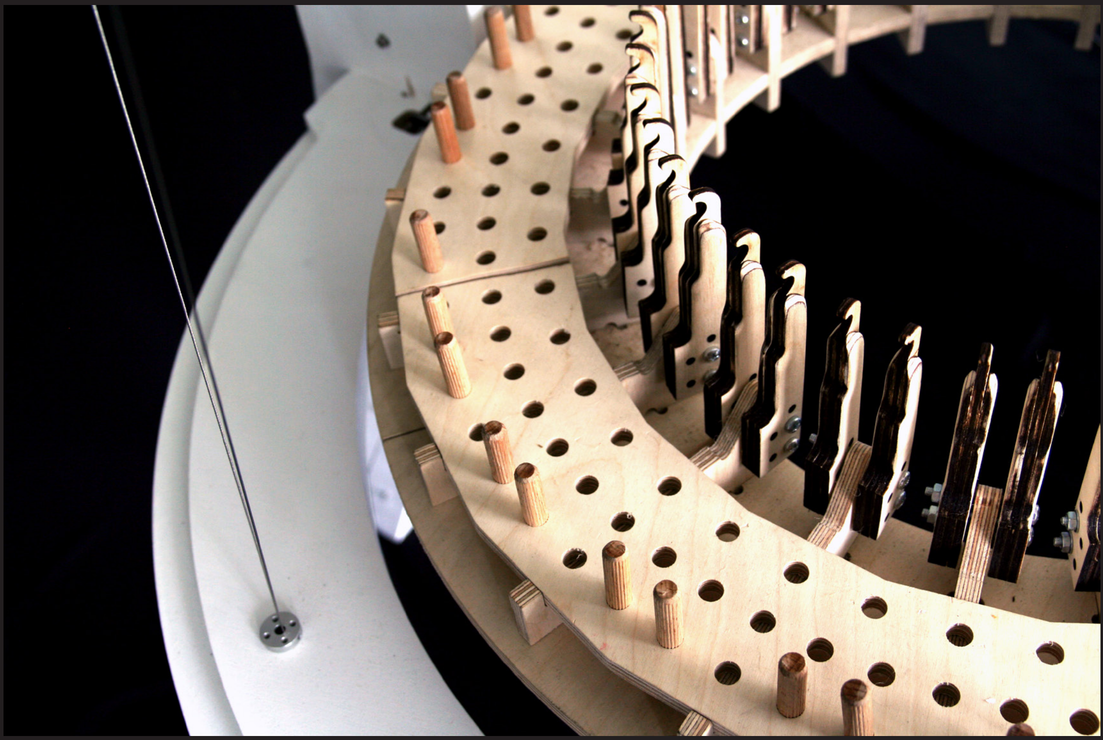


Figure 179 Loom construction details; visualisation Suarez (2018)

Figure 180 Loom setup →



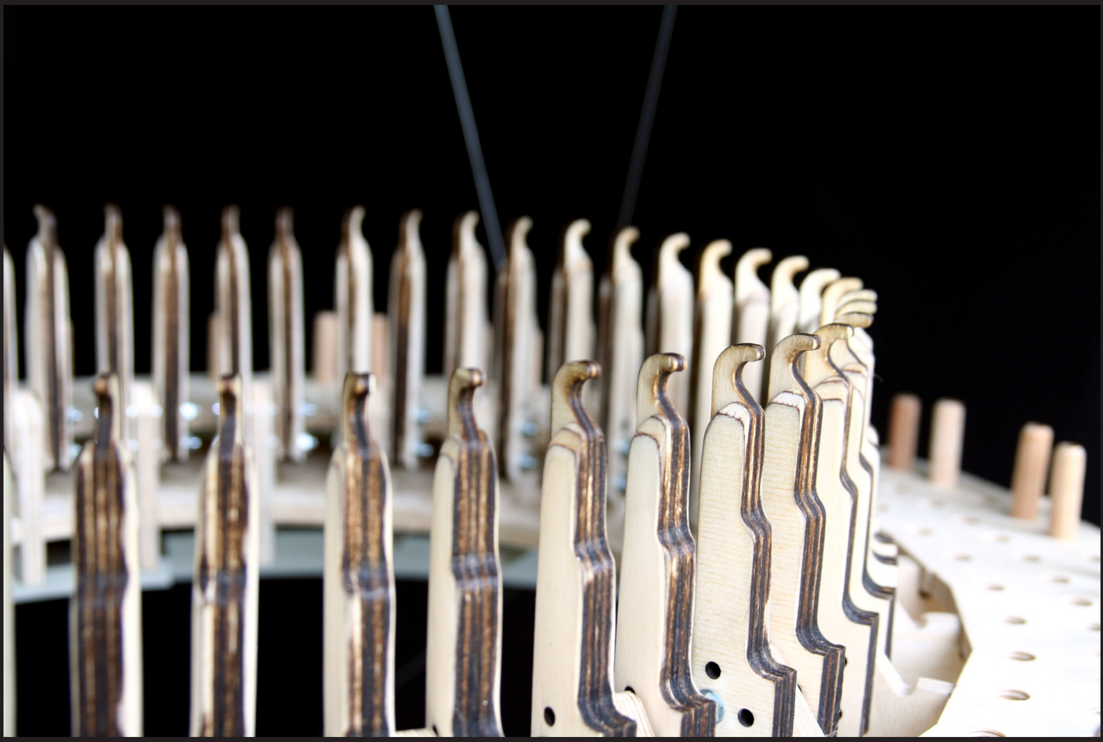


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Figure 181 Loom detail 1
Figure 182 Loom detail 2

3. Bioreactor

In order to apply the bacterial solution an enclosed, but not sterile, container had to be conceived. The design is based on the findings of the small-scale treatment system test outlined at the beginning of the chapter. The bioreactor (Figure 183 - Figure 189) incorporates improvements to the liquid circulation system as well as a different rotation system for the specimen due to the increased loads.

Custom-fabricated waterproof acrylic top and bottom parts, connected by a flexible transparent polyvinyl sheet, define the general volume of the reactor. The dimensions of the top and bottom parts are fixed; however, the distance between the two parts can be adjusted if necessary, which increases the overall volume. In contrast to the small-scale test setup, the container is static in order to reduce construction complexity and moving parts. A rotating plate, held by six ball transfer bearings, onto which the sample (Figure 183, A) to be treated is mounted, provides the rotation (around the vertical axis) during the process.

The sprinkler system was redesigned to be compatible with a 1.1 Bar, 220V Pump (Hozelock 2826, Figure 183, D) and a 14 mm pipe system, which increased the pressure as well as the flow rate compared to the small-scale test, to match the change of scale. The bi-directional sprinkler system intended to irrigate the outside as well as the inside of the structure, informed the design of the container. The circular area (Figure 183, A) allows the sample to rotate around a vertical axis, whereas the protrusion houses the irrigation system responsible for treating the outside of the sample (Figure 183, C1/2). In contrast to the previous small-scale test, two parallel circulation systems were installed to avoid pipe clogging (Figure 183, B1/C2). This could occur when the pipes were used for both liquids (the bacterial solution and the calcifying solution) and the residual active bacteria triggers the calcification within the tube system. Furthermore, each system has two branches, each with five sprinklers (Figure 183, F) attached, so that a more homogeneous treatment from both sides is achieved.

→

Figure 183 Incubator scheme

Figure 184 Explosion drawing base structure and bioreactor

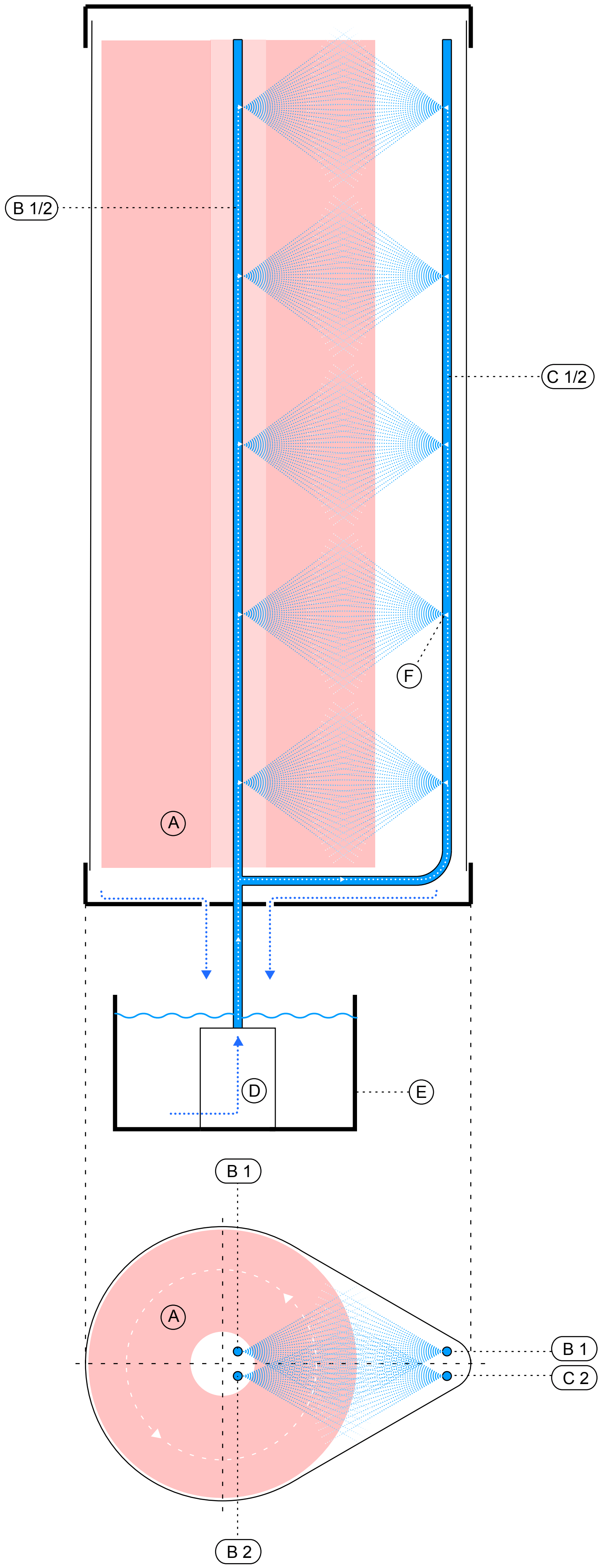
Figure 185 Construction drawing topview

Figure 186 Bioreactor front view

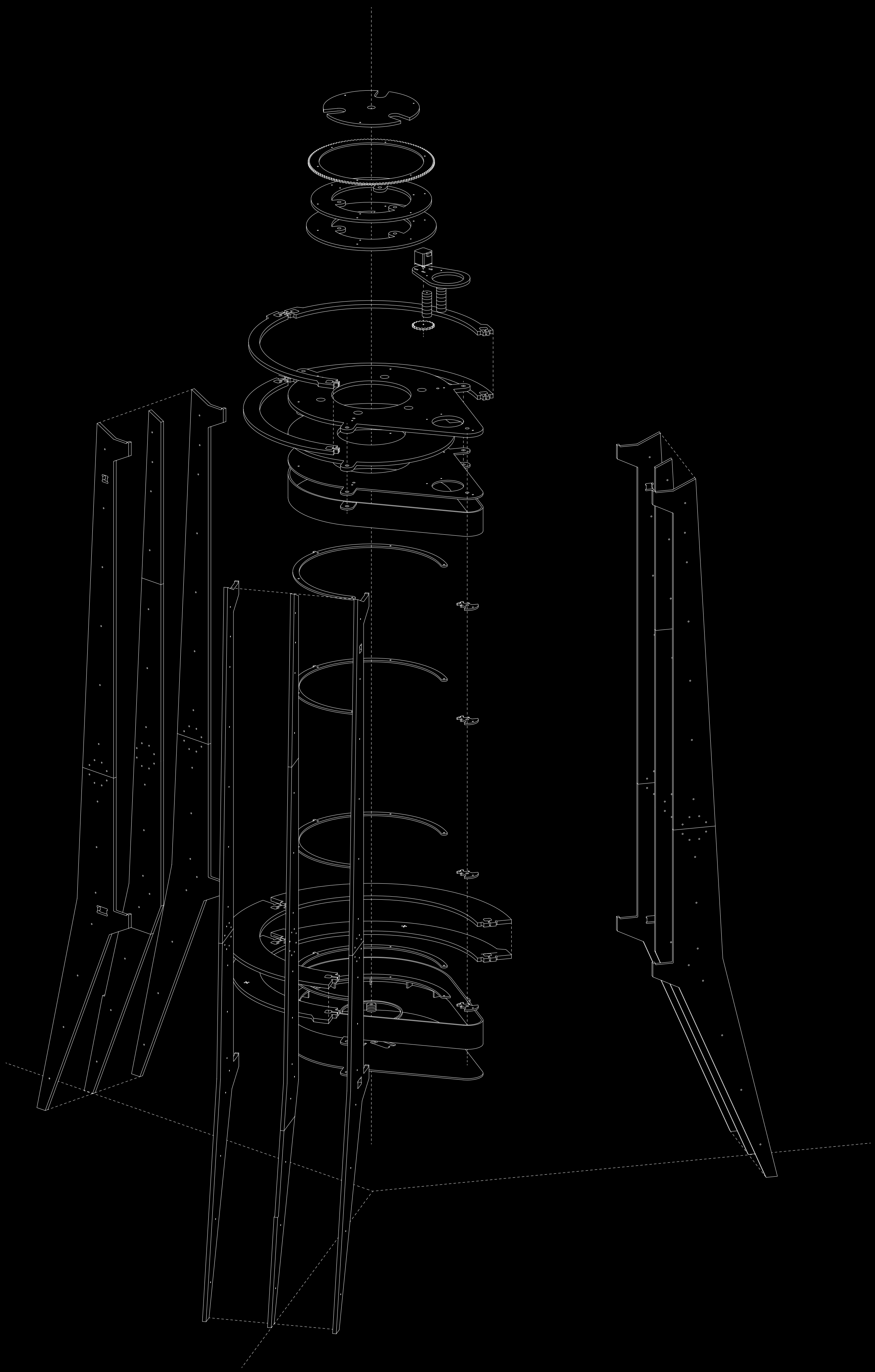
Figure 187 Bioreactor side view

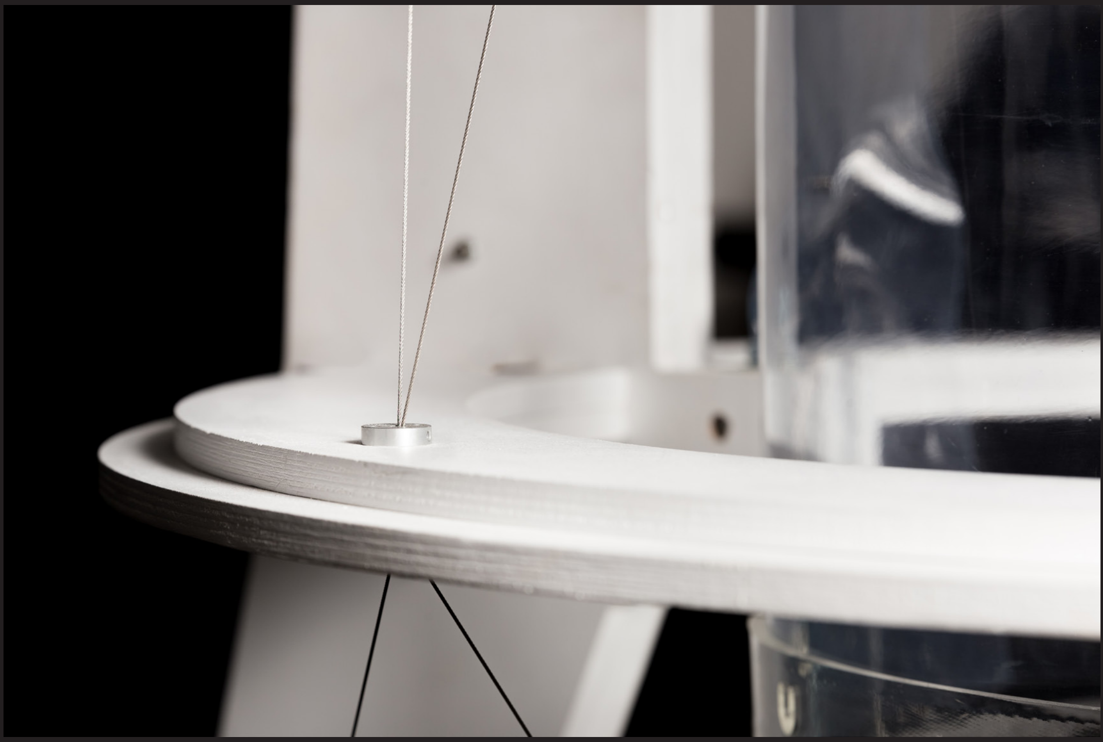
Figure 188 Base structure detail

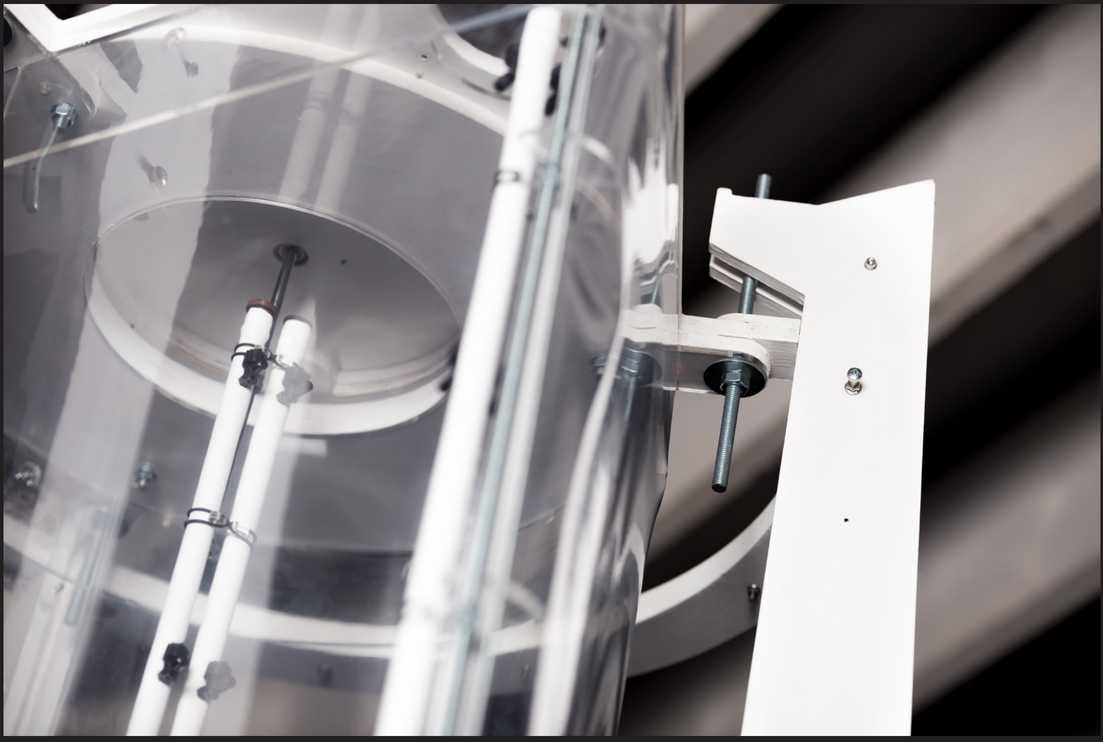
Figure 189 Bioreactor and irrigation system detail



B 1/2
C 1/2
F
A
D
E
B 1
A
B 1
C 2
B 2







Fibrous substrate development

During the structural tests of Etude 3 it was found that jute fibre delivered the best results. The coarse fibre finish generated an increased surface, which contributed to calcite deposition as well its cross-linking properties. Furthermore, jute offers an abundant, fast-growing resource which is available in large quantities, as it is commonly used for packaging or rope production. This material was therefore chosen for implementation in the case study project.[26]

Based on the structural test results of étude 3, a parallel bundled fibre array was considered for the production of the base material. Besides delivering the best results for a compressive load case (79.6 N/cm2 compression), this fibre configuration was found, after consultation with Eurecat (textile fabrication consultant), to be the simplest and fastest to produce on a larger scale.

In order to confine the parallel fibres, a sleeve had to be generated around the bundled fibre strands. The challenge was thus to find a process which provides full control over the permeability of the sleeve construction (Figure 190). The sleeve structure, as well as the fibre density, needed to be controlled, as these two factors relate directly to the material's potential liquid permeability. Simultaneously, the fibre density and sleeve structure influence the material's flexibility which, in turn, defines the behaviour during and after the knitting process.

Initial material studies showed the bundled jute thread's poor "knit-ability" due to its lack of elasticity, as well as a comparably low flexibility. However, a loose parallel fibre array provided a small amount of elasticity while allowing for sufficient flexibility.

Substrate manufacturing

In general, tubular textile materials can be generated with technologies such as circular knitting, circular warp knitting or braiding; however, each process demands specific machinery as well as distinct material quality. A variety of different factors, such as speed, material behaviour and density, define the overall behaviour of the sleeve construction. Therefore in order to find an optimal solution a series of samples were manufactured, investigating different textile techniques, machinery and speed of production, as well as the range in diameter (maximum, minimum) achievable in order to optimise the overall material consumption. Additionally, the aim was to find a configuration and suitable machinery which at the same time allowed the seamless fabrication of a graded material.

26 Further preliminary tests were undertaken to determine the specific jute fibre selection and constellation (see appendix J)

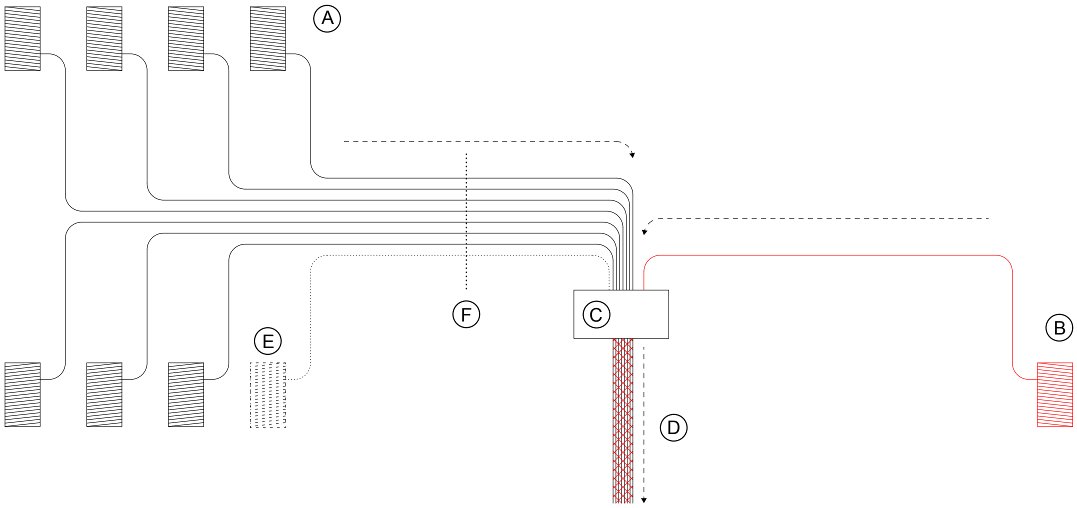


Figure 190 Fabrication scheme

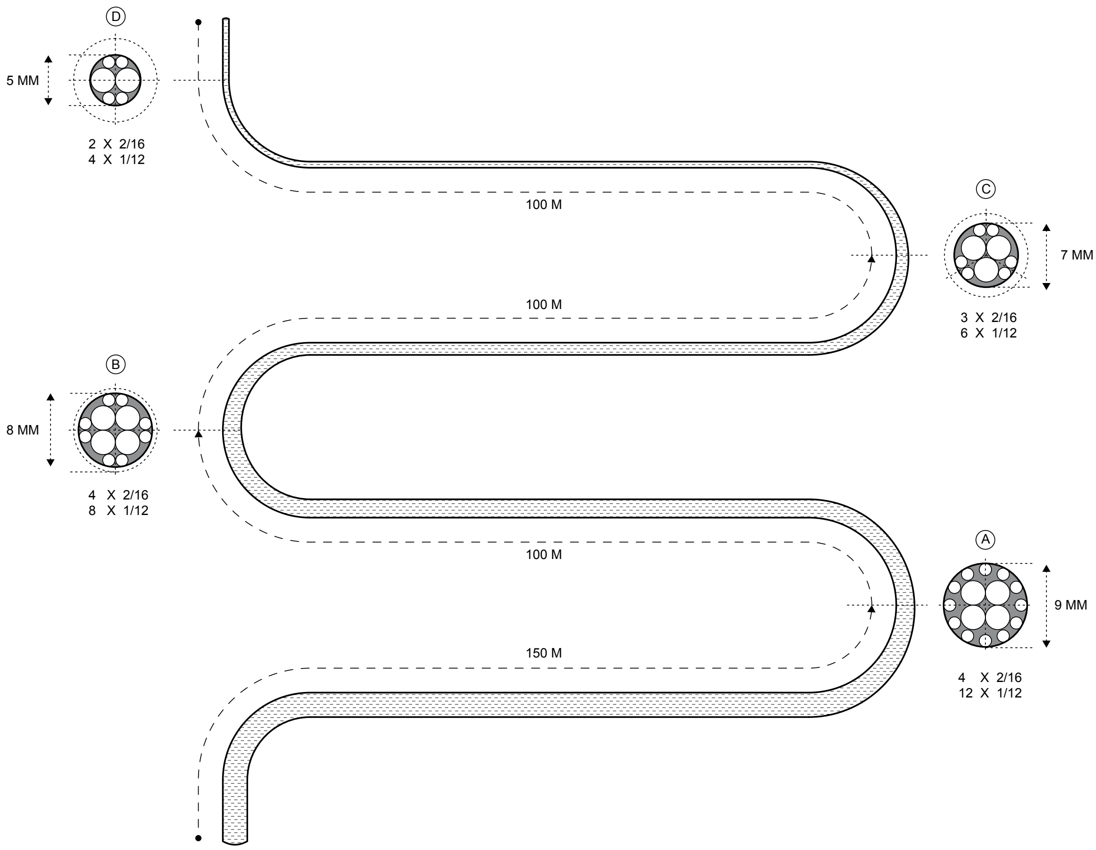


Figure 191 Substrate gradient and internal structure

In this specific case, a gradual decrease in diameter throughout the continuous base material was developed, which would allow an increase in the material deposition in the base section while decreasing it in the top area, in relation to the vertical load case (Figure 191). This material optimisation on the material level accounts for a material saving of approximately 28.8 per cent throughout the structure (Figure 192).

The fabrication scenario (Figure 190) was applied for each tested manufacturing method. It consisted of individual yarns simultaneously feeding into the sleeve-generating machine. This system enables the cutting of individual yarns during the manufacturing process, thus generating a controlled material gradient without interrupting production.

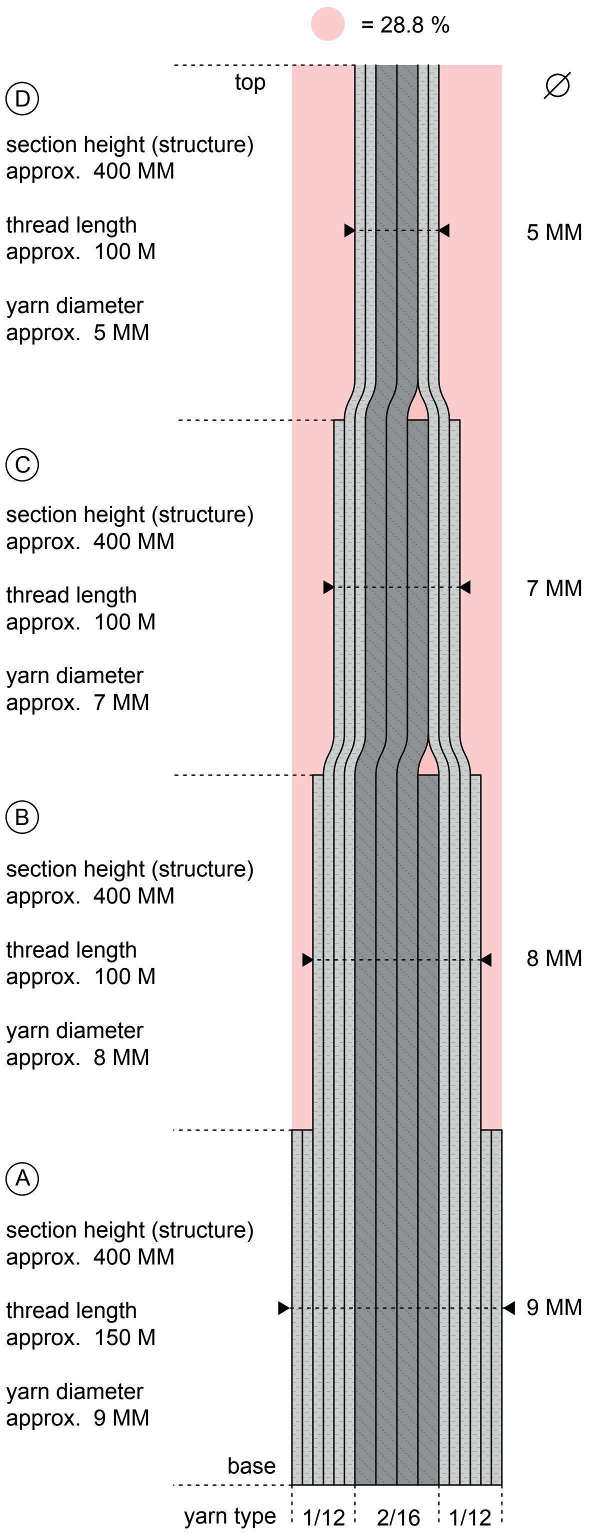


Figure 192 Substrate overview (global)

Manufacturing system trials:

Previous discussions and consultations with the technicians from Eurecat ahead of the visit led to a selection of potential manufacturing methods being considered. A schedule of two days of explorative sample production followed by two days of production had been agreed.

The available machinery consisted of:

1. 12 needle warp-knitting machine in 12 and 6 needle configurations (TEXMA TC2-12,(Figure 196)

2. Braiding machine

3. Ribbon-weaving machine (Jakob Müller NFN-28,Figure 193)

In a two-day workshop, the potentials of each machine were explored and evaluated. Factors considered for selecting the production method were:

- Sleeve quality

- Flexibility, knit-ability

- Aperture and permeability

- Material consumption / efficiency

- Redundancy and durability

- Maximum and minimum potential diameters

- Production speed

Figure 193 Jakob Müller NFN-28

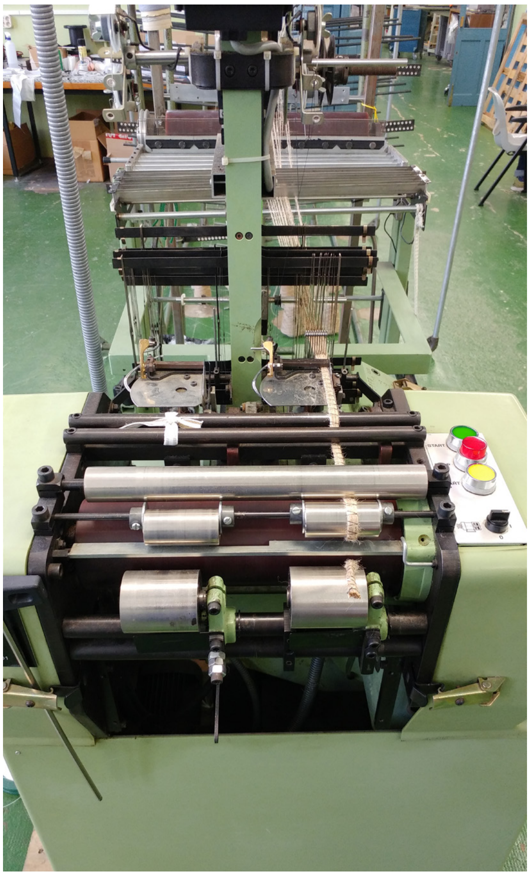


Figure 194 Jakob Müller NFN-28 ribbon-weaving process

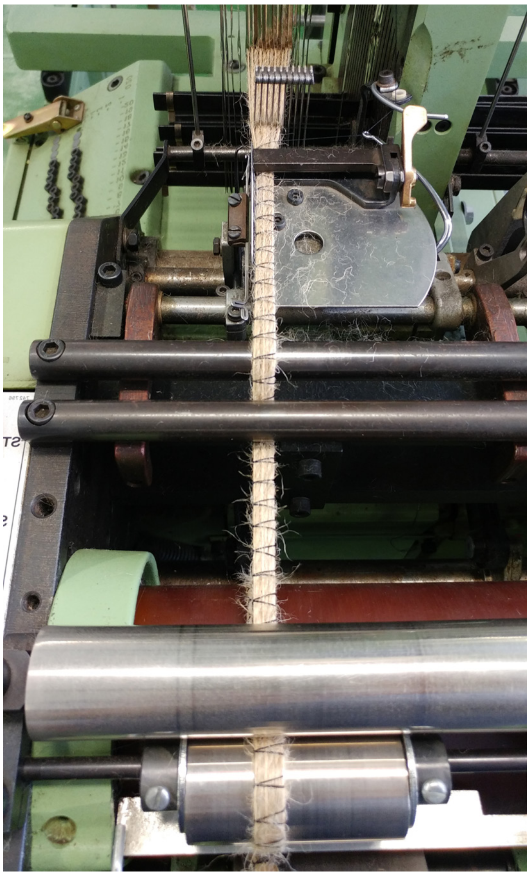


Figure 195 Jakob Müller NFN-28 ribbon-weaving detail

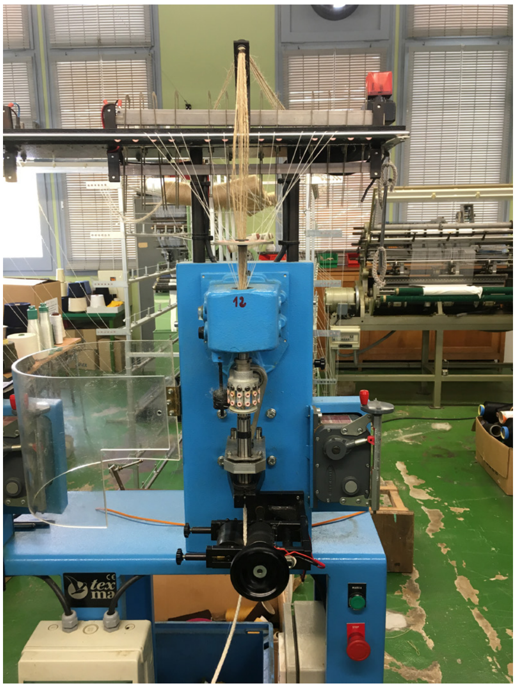


Figure 196 TEXMA TC2-12

Figure 197 TEXMA TC2-12 detail

Results

Initial tests on the machines showed that the six-needle warp knitting process (TEXMA TC2) was unable to process the intended diameter. Likewise, the braiding machine did not prove viable for the project either, due to the time-consuming production process and the tight sleeve material. Therefore, investigations into these two processes were discontinued at an early stage.

However, intensive material tests were executed on the 12-needle configuration of the warp knitting machine (TEXMA TC2) as well as the weaving machine (Jakob Müller NFN-28).
In contrast to the six-needle configuration, the 12-needle machine enabled a thicker core material insertion. At the same time, it was possible to knit with just six of the 12 needles, which reduced the density of the sleeve. The main objective was a gradual increase in the core material thickness by successively adding more parallel jute strands. In order to test the reliability of the production method, approximately four metres were manufactured for each step of increase in the diameter.

It could be observed in Test 1 (Table 5) that lower densities (max 2 x 2/16 and 4 x 1/16) were more suitable for this mode of production, as the increased core density interfered with the knitting needles, starting to cause failures with a density of 2 x 2/16, 5 x 1/12. The method delivered reliable results for thin threads, providing good flexibility and knit-ability while providing a high production reliability due to the 12 individual yarns used for the sleeve. However, a diameter of just 6mm could be achieved reliably. Furthermore, the dense sleeve construction was proven to consume too much material in comparison to the amount of filling, thus providing an unbalanced ratio between core and sleeve material usage.

In order to reduce the material consumption of the sleeve, a series of tests was executed using just six active needles on the 12-needle machine. Test 2 (Table 6) increased the aperture and permeability of the sleeve but caused issues in relation to the reliability of the production method, with issues occurring from 2 x 2/16 and 2 x 1/12.

1	Machine type	Process	Material	
	TEXMA TC2	Warp knitting 12 Needles	Sleeve	Cotton (30/1) 2 threads
			Core	Jute 2/16 (1.5 mm),1/12 (1mm)

	1	2	3	4	5	6	7	8	9	10	11
2/16	0	1	2	2	2	2	2	2	2	2	3
1/12	1	0	0	1	2	3	4	5	6	7	7
∅	4 mm	4 mm	4 mm	6 mm	5 mm	6 mm	6 mm	7 mm	5 mm	7 mm	9 mm

Table 5: Test 1, warp knitting samples, 12 needles

2	Machine type	Process	Material	
	TEXMA TC2	Warp knitting 6 Needles	Sleeve	Cotton (30/1) 2 threads
			Core	Jute 2/16 (1.5 mm),1/12 (1mm)

	1	2	3	4	5
2/16	1	1	2	2	2
1/12	0	1	1	2	3
∅	3 mm	4 mm	4 mm	5 mm	5 mm

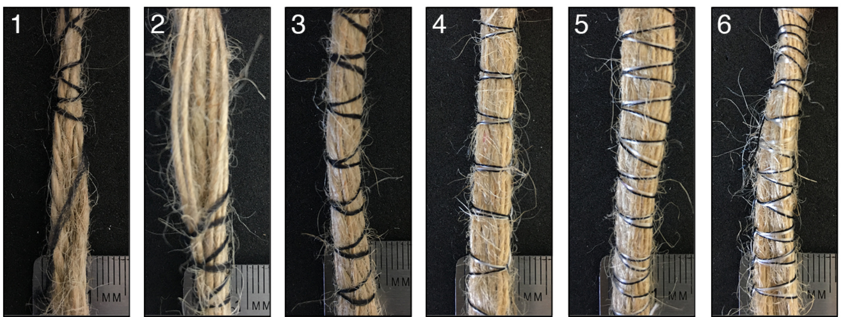
Table 6: Test 2, warp knitting samples, 6 needles

Test 3 (Table 7) involved a ribbon-weaving method which enabled the processing of up to 4 x 2/16 and 12 x 1/12, thus achieving a diameter of up to 9mm reliably. The first tests were with conventional polyester thread as a sleeve (Sample 1,2,3, Test 3), which was liable to fail during continuous manufacturing. By incorporating a high-tensile polyester thread, this issue could be resolved. The sleeve displayed a very high permeability as well as confining the threads sufficiently at a very low rate of material consumption.

Moreover, the machine allowed a variation of three speed settings, which influenced the density of the sleeve. Samples 1,2,3 (Test 3) explore the different speeds and their relation to the global behaviour. It could be observed that an increased manufacturing speed led to a denser sleeve. Furthermore, the final piece tended to curl, which influenced the handling negatively. The best results were achieved with the minimum speed setting, which was, however, still faster than the 12-needle machine.

Ultimately, the weaving process on the Jakob Müller Machine (NFN-28) delivered the best results in relation to the permeability of the sleeve and its bendability and knit-ability. At the same time, the material consumption for the sleeve could be reduced to a minimum while achieving fast and reliable production. The process also enabled a seamless interaction with the core material, enabling a smooth transition while gradually reducing the core material content in order to manufacture a graded material. The overall continuous production length was approx. 450m (Figure 199), with four differentiated core constructions (Figure 191).

	Machine type	Process	Material	
3	Jakob Müller NF 42 2/48	Weaving	Sleeve	Polyester
			Core	Jute 2/16 (1.5 mm),1/12 (1mm)



4	2/16	4	2/16	4	2/16	4	2/16	4	2/16	4	2/16
0	1/12	6	1/12	8	1/12	12	1/12	12	1/12	12	1/12
∅	8 mm	∅	7 mm	∅	8 mm	∅	8 mm	∅	8 mm	∅	8 mm
	MIN		MIN		MIN		MIN		MED		MAX

Table 7: Test 3, weaving samples

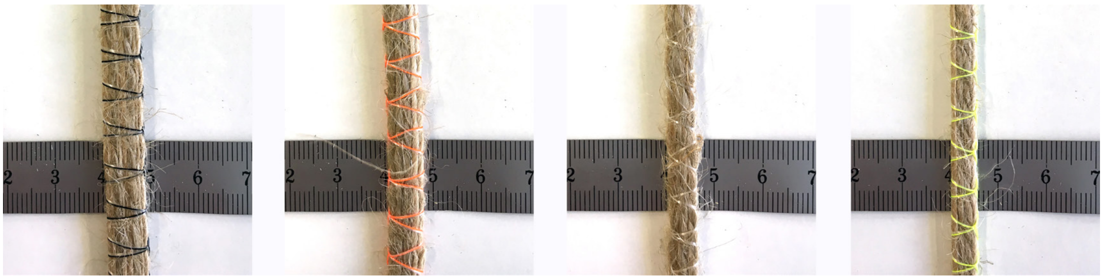


Figure 198 Graded diameter throughout the textile material

Figure 199 Finished continuous substrate; colours indicate change in material diameter

Knitting process

The construction of a conventional knitted fabric depends on a single continuous yarn linked by a pattern of inter-connecting loops, which accounts for its stability as well as its elastic behaviour.

In the context of architecture this material system is usually used for (tensile) membranes, where its bi-directional elasticity enables complex double curved surfaces (Thomsen et al. 2015). Recent advances in the field of composites have investigated knitted structures as reinforcement embedded in a resin matrix (De Araujo et al. 2011; Pamuk 2016; Duhovic & Bhattacharyya 2011). In these cases, the structural system can be described as a shell structure.

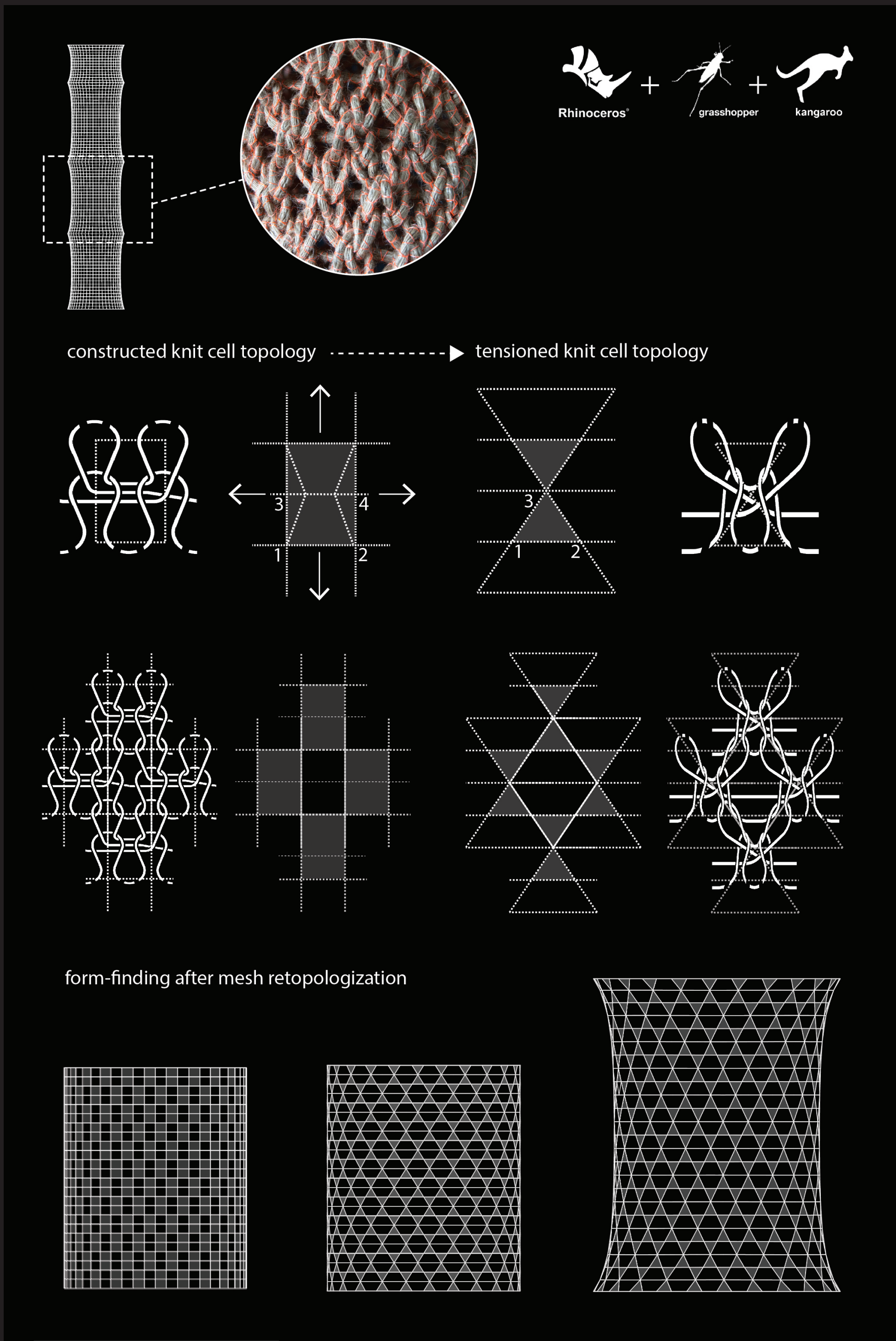
In both cases, however, the thickness of the knitted fabric does not usually exceed approx. 2mm due to the thin yarns used for manufacturing. Therefore the fabric itself is only able to perform as either a membrane or a shell (embedded in a resin matrix). However, the system changes with an increase in yarn diameter and the augmentation of the knitting pattern, in inverse proportion to the overall dimension of the fabric. This produces a situation in which the individual yarn within a textile structure is able to sufficiently bear compressive loads: the structural system can thus be perceived as a (textile) space frame.

Generally, conventional knitting machines operate within a range of up to around 5 mm of yarn thickness, and struggle to process very coarse, non-uniform yarns. Therefore, a hand-knitting process was applied to manufacture the textile structure. A series of small-scale tests helped to analyse the knitting patterns in relation to their geometry beforehand. It was observed that the structural geometry of the patterns, as well as the overall shape of the structure, changes upon tensioning. The goal of this work was to apply patterns which generate (upon tensioning) a combination of horizontal connections and a diagrid structure, resulting in a triangulation and thus achieving a stiff, braced structural system.

Through a simulation using Grasshopper and Kangaroo Physics for Rhino, the final shape was approximated (Figure 200), Figure 201 Figure 202).

For the manual knitting process, the knitting loom was mounted onto the modular base structure (Figure 180). The yarn could be fed from the top of the structure (Figure 203) while the person knitting was able to work in a comfortable seated position (Figure 204). Furthermore, the loom could be horizontally rotated to maintain an ergonomic knitting position.

Figure 200 Knitting pattern analysis (Suarez 2018) →


Rhinoceros
grasshopper
kangaroo
constructed knit cell topology
tensioned knit cell topology
3
4
1
2
3
1
2
form-finding after mesh retopologization

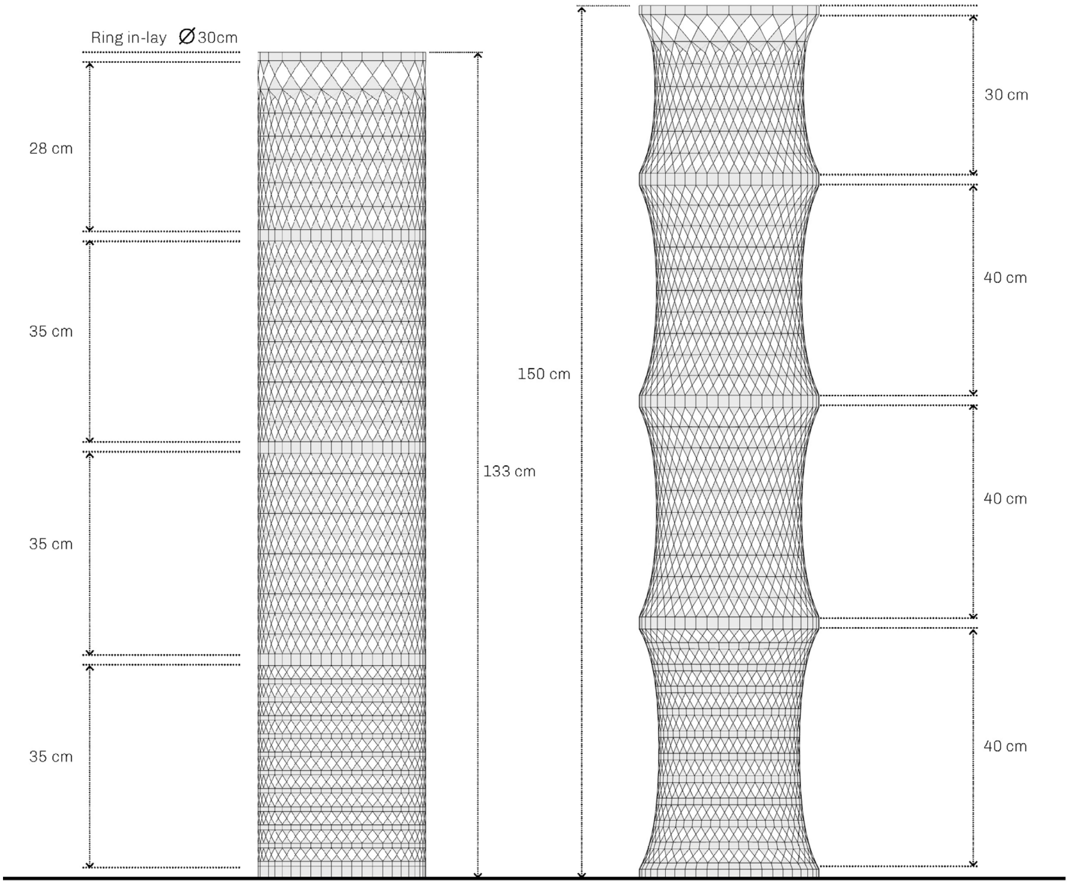


Figure 201 Tensile form-finding process (Suarez 2018)

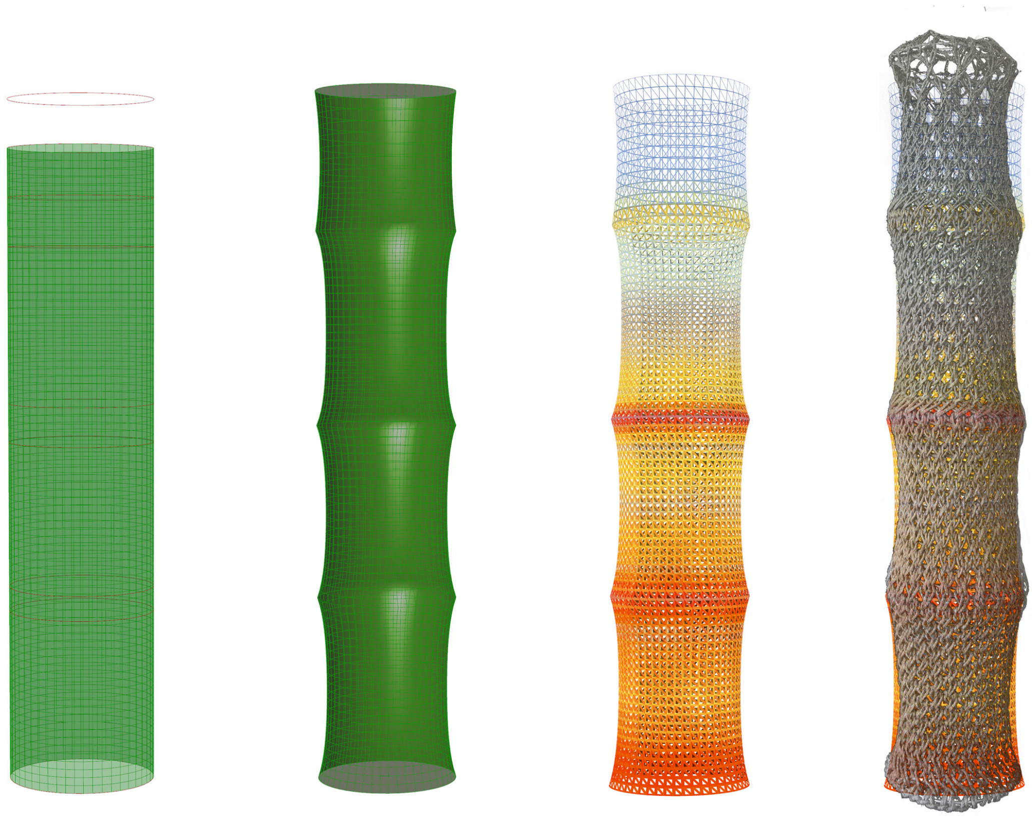


Figure 202 Structural analysis (Suarez 2018)

Figure 203 Knitting process; top view

Figure 204 Knitting process; side view

The knitting procedure worked in a similar way to conventional hand-loom knitting. The yarn is wrapped around the pegs for one continuous round. A second round is applied and gradually interlocked with the row below using a knitting needle (Figure 205). This process demands a high level of dexterity and concentration, as the more complex patterns are required to drop, double or transfer loops in a predetermined pattern. At the same time, it is crucial to maintain the tension applied during the process to avoid loops that are too loose or too tight. Failing to do so may result in either the pattern not being knit-able, an unbalanced pattern in relation to the whole structure causing the fabric to set asymmetrically, or even the unravelling of the whole structure in the case of an open loop.

In order to maintain a similar diameter throughout the structure, five 8mm stainless steel rings (approx. 300mm diameter) were inserted while knitting the structure. The insertion technique has been specifically developed for this application, enabling continuity during the knitting process. The rings are located at the bottom and the top as well as in between changes of pattern (approx. every 400 mm) (Figure 207).

Upon completion of the knitting, the finished structure was taken off the loom and tensed using an internal substructure, which consisted of three 12 mm threaded rods and a base and top-plate. Once the two plates were connected to the sample, the rods (approx. 1700mm each) could be placed vertically in between the plates allowing the structure to be tensed gradually by fastening individual bolts on the threaded rods. The tensing of the structure transforms its shape as well as its geometrical pattern (Figure 201). The overall shape sets into a minimal surface in relation to the knitting patterns and the force applied during tensing, restricted by the metal rings which apply an internal force that counteracts a thinning in the middle section. It is important to mention here that the base material (jute yarn) as such does not intrinsically have any of the elastic properties which are sought when trying to achieve tensile minimal surfaces. However, due to the knitted structure and the resulting geometry the finished fabric becomes stretchable, even though the material it is made of is not. Once the tensing is finished the structure is mounted into the bioreactor for further treatment (Figure 211 - Figure 217).

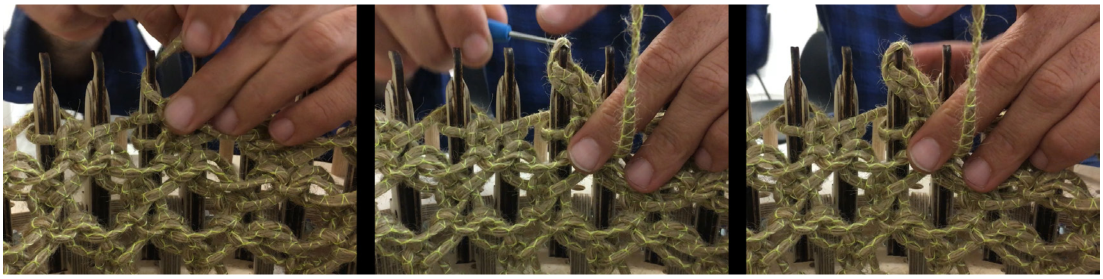


Figure 205 Knitting process detail

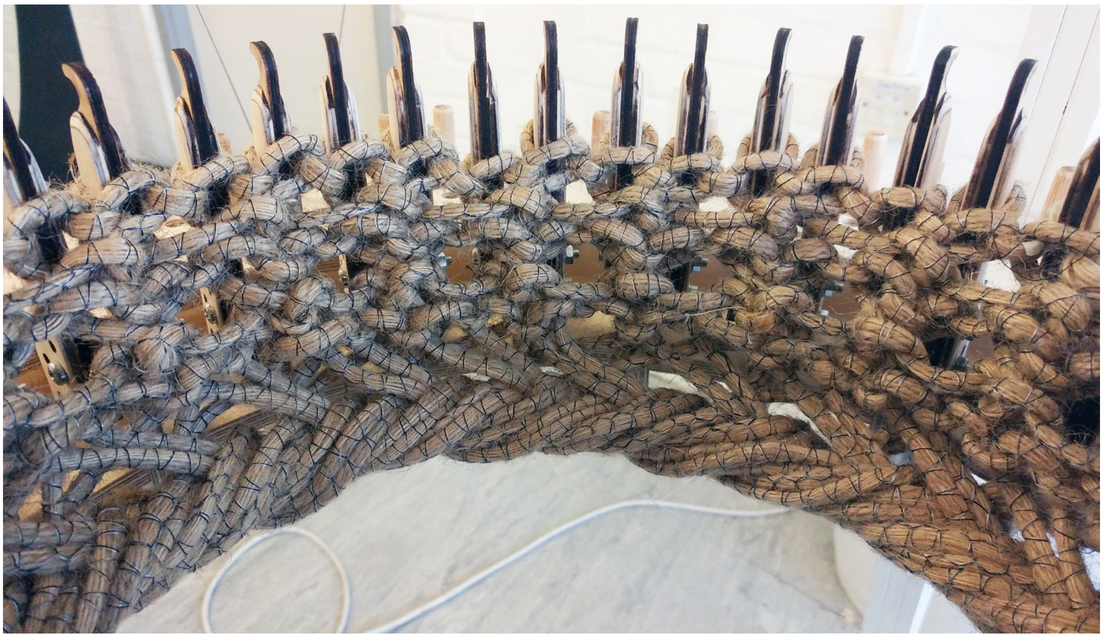


Figure 206 Loom and structure

Figure 207 Compressive rings insertion

Figure 208 Knitting patterns gradient; continious materiality and topology, varying geometry

→

Figure 209 Inside view textile structure

Figure 210 Pattern gradient

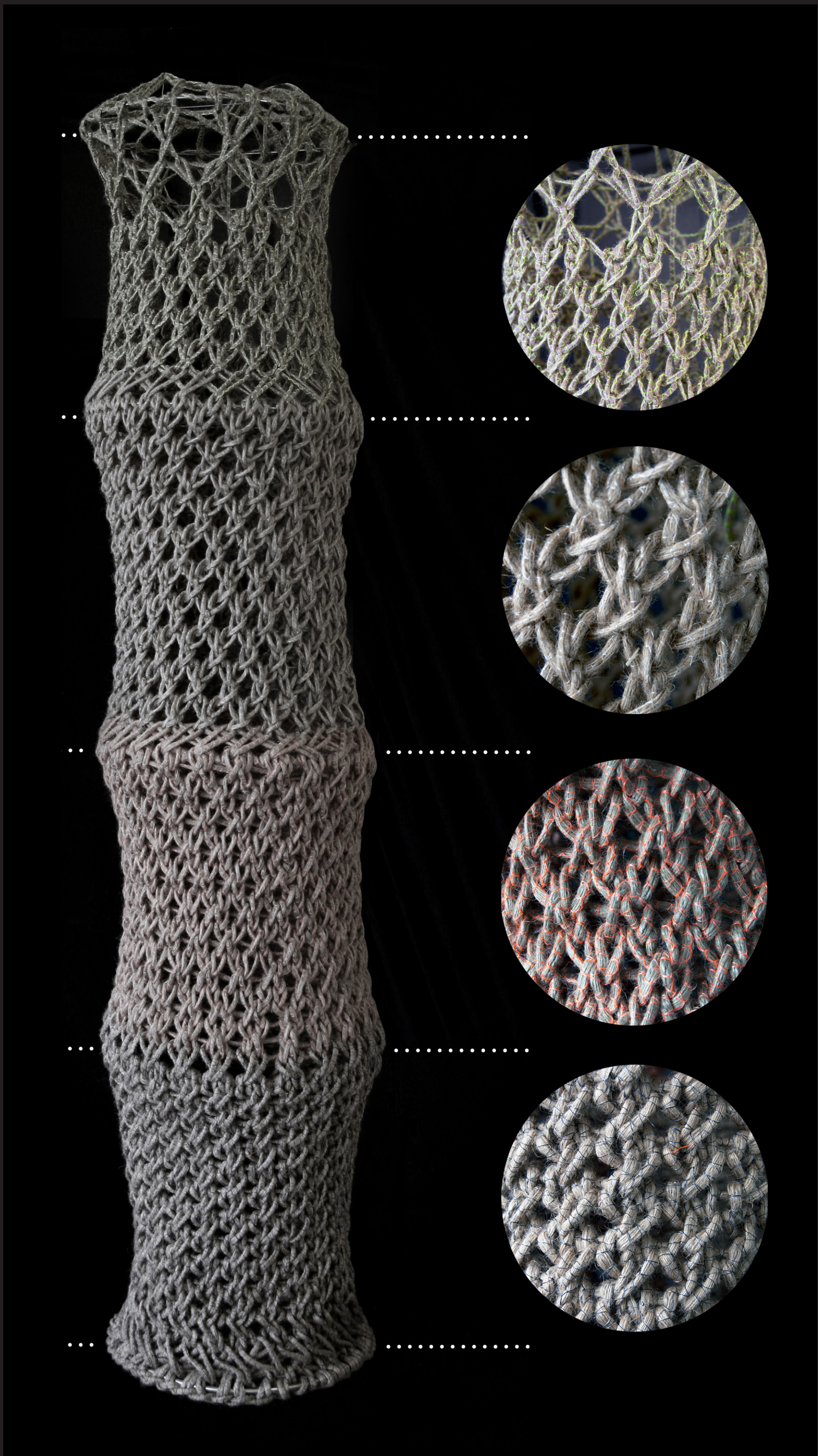
Figure 211 Bioreactor with textile structure; front

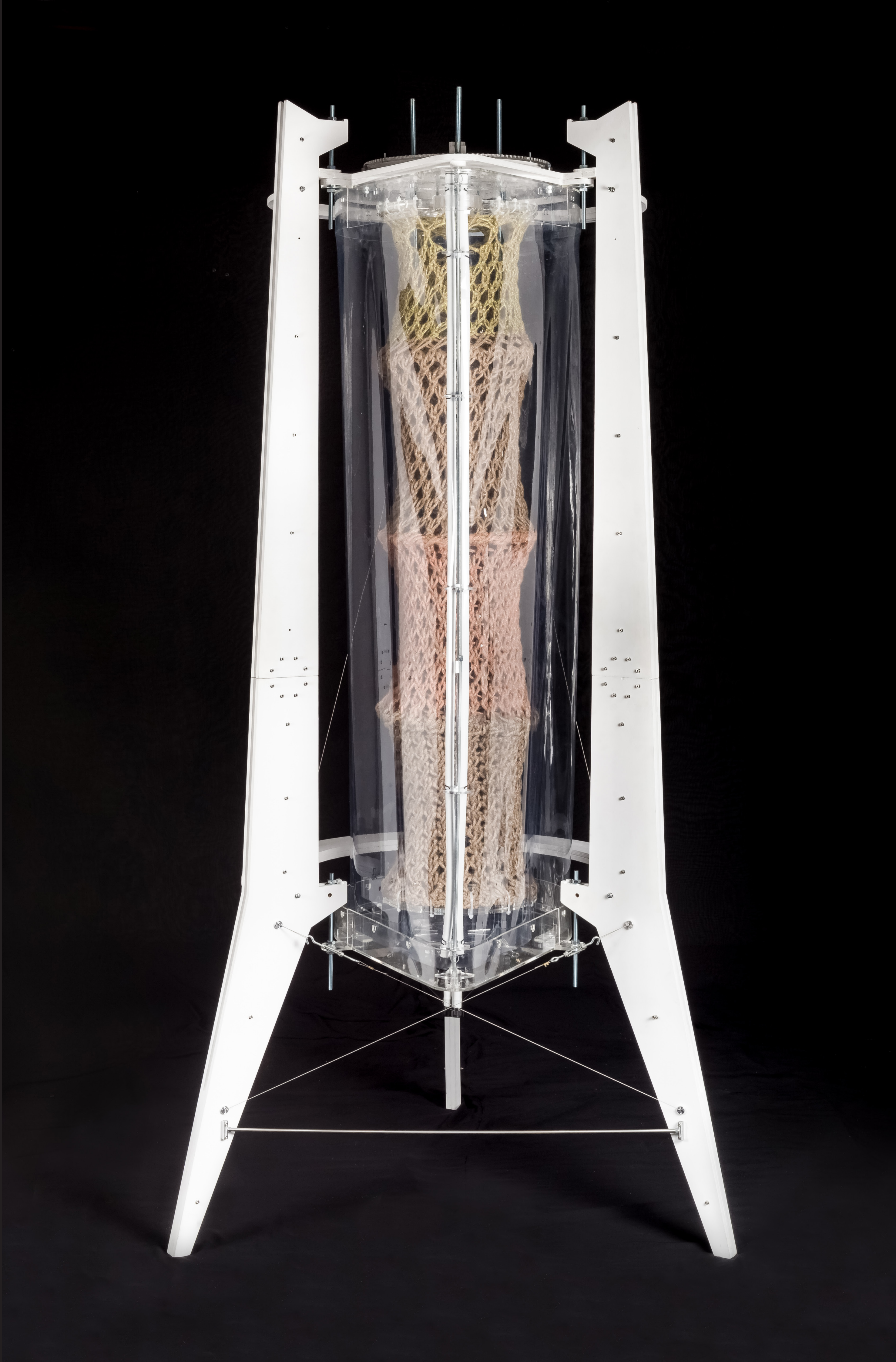
Figure 212 Bioreactor with textile structure; side

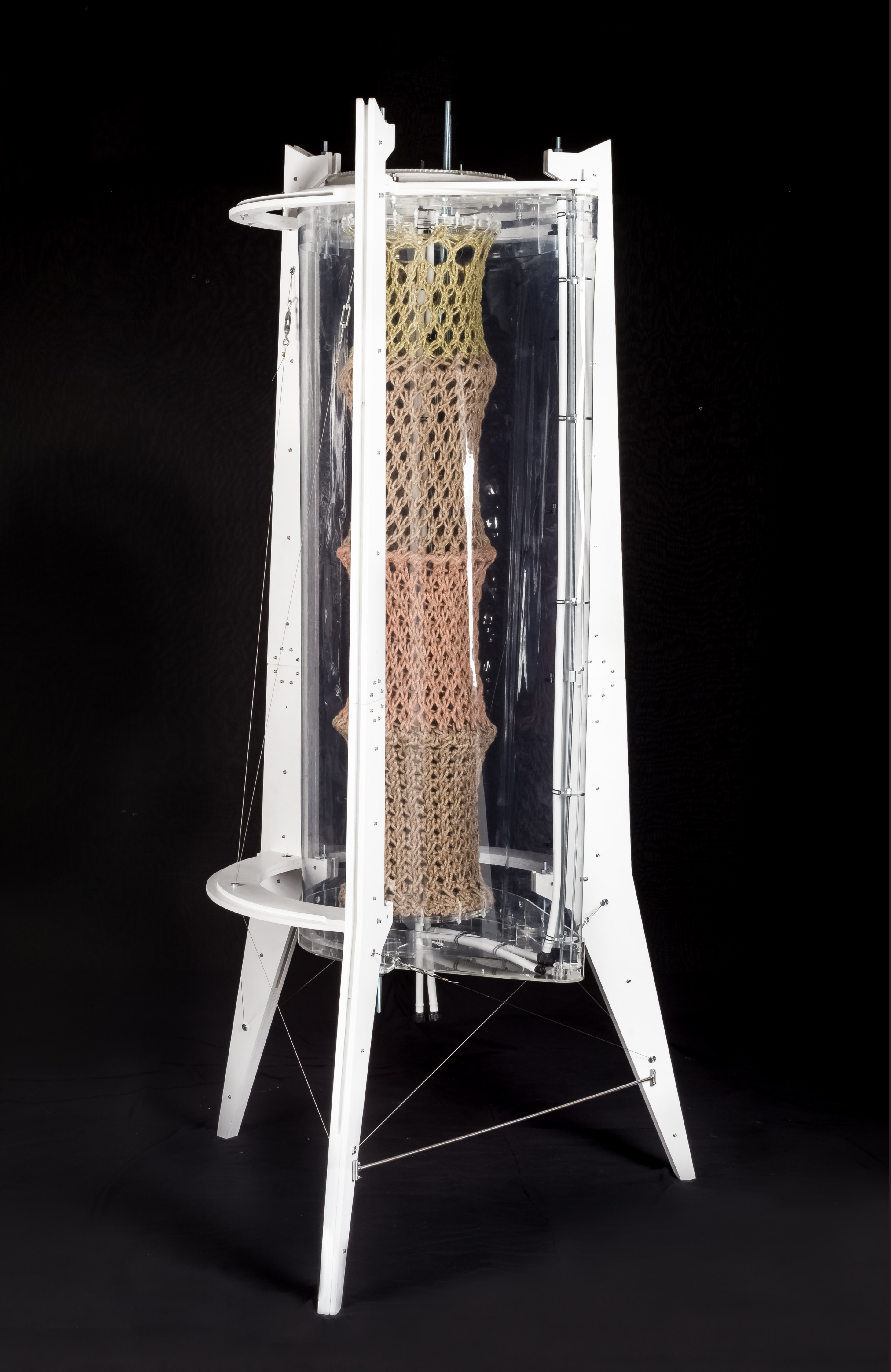
Figure 213 Bioreactor with textile structure; detail 1
Figure 214 Bioreactor with textile structure; detail 2

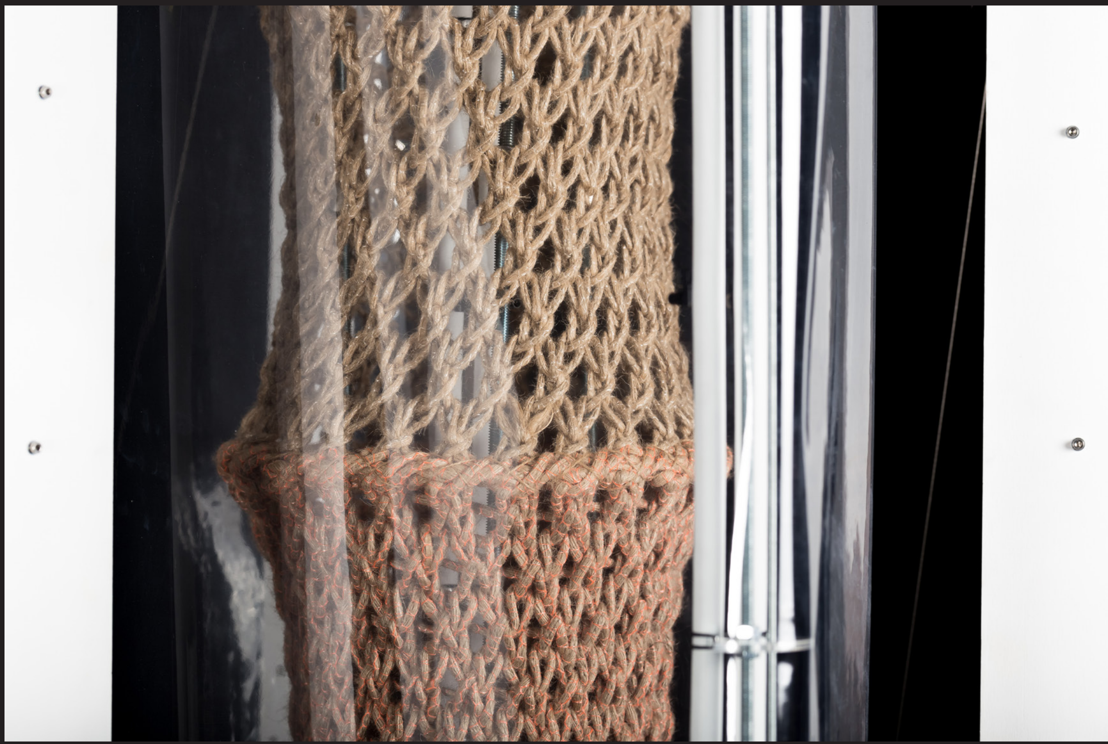
Figure 215 Bioreactor with textile structure; detail 3
Figure 216 Bioreactor with textile structure; detail 4

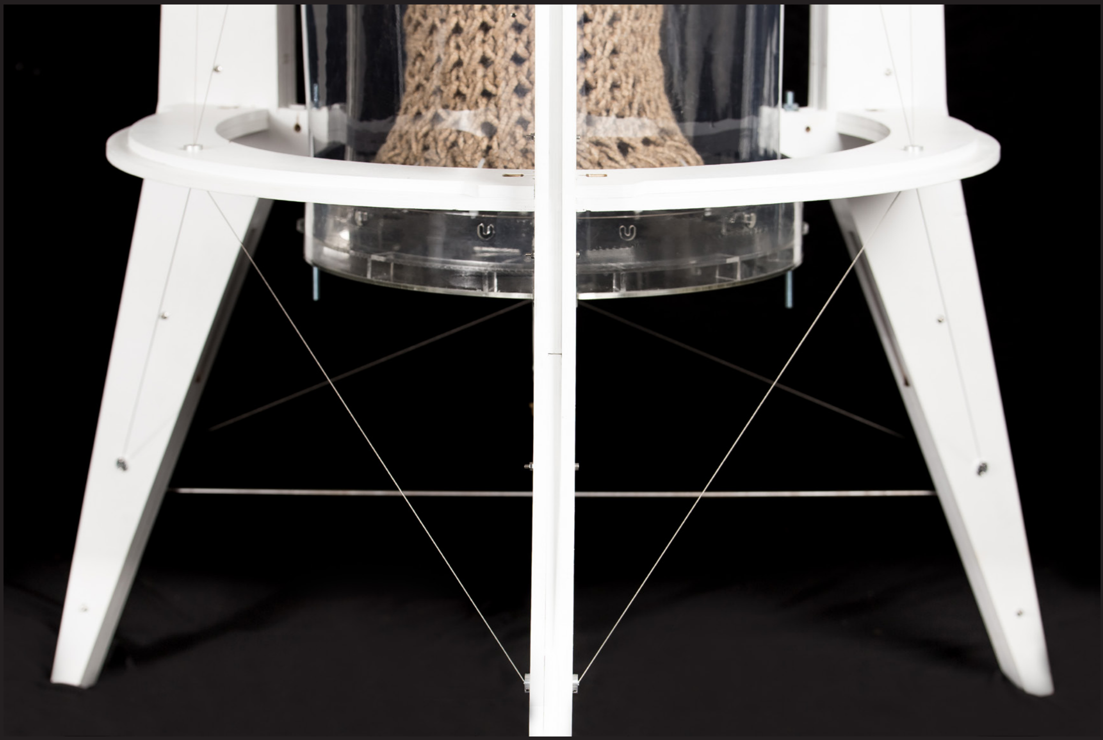
Figure 217 Bioreactor with textile structure; detail 5

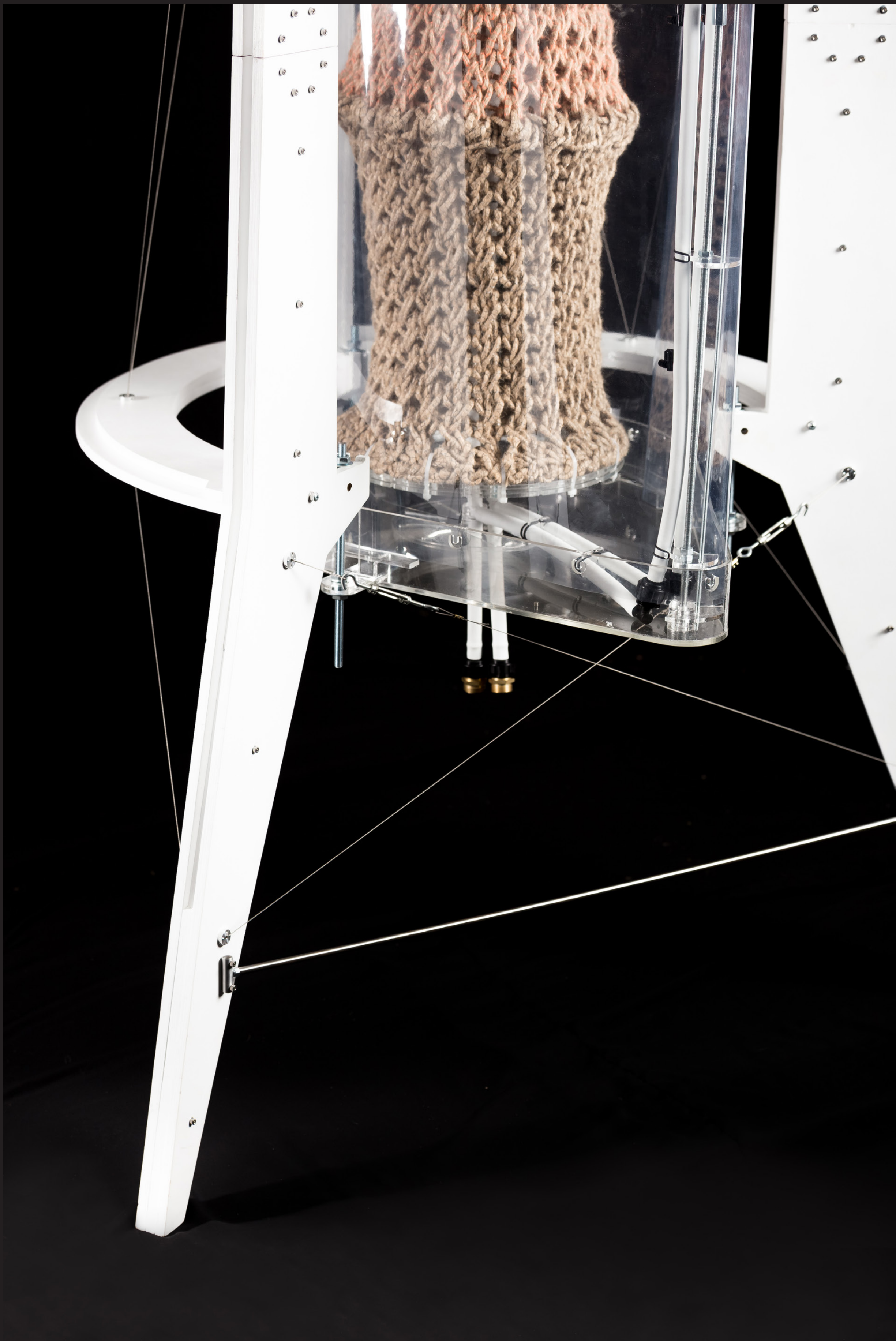












Bacterial treatment

The bacterial solution and the calcifying solution were mixed separately before the treatment. Each batch of bacterial solution contained around 30g of freeze-dried *Sporosarcina pasteurii* bacteria dissolved in 20l of water.

The preparation of the solutions is similar to that in previous experiments (Biocalcis protocol); however, the ratio of bacteria was slightly increased as the treatment took place on site, with several factors, such as water quality or temperature, potentially influencing the bacterial activity.

While slowly rotating (approx. 1 rotation / 2 min.) the structure was initially sprayed with the bacterial solution for three periods of five minutes with five-minute breaks in between treatments (Figure 218 - Figure 219). This allowed the solution to gradually permeate the whole textile. A 20-minute break after the bacterial treatment provided sufficient time for the bacteria to adhere to the fibres, followed by the second treatment with the Urea/Calcium chloride solution in order to trigger the calcification process. For the calcification cycle the same interval of three five-minute periods with five-minute breaks in between was applied. During the second cycle the first indication of calcification occurred and a significant improvement in the material's rigidity could be observed. Over a period of three days, eight treatments were executed (day 1: 2 treatments, day 2: 3 treatments, day 3: 3 treatments), followed by a rinse with clear tap water for approximately 30 minutes.

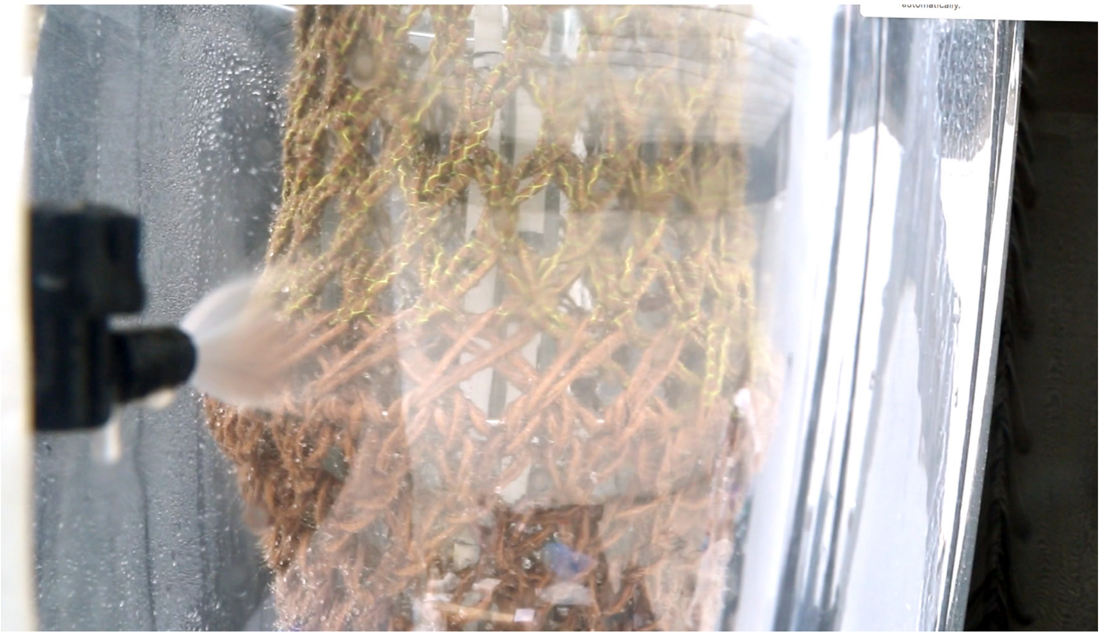


Figure 218 Treatment process, detail 1

Figure 219 Treatment process, detail 2

Results

The treatment resulted in a gradual build-up of a bacterial calcite matrix throughout the fibrous structure (Figure 220, Figure 221). The textile structure was removed from the bioreactor after one day of draining. After air-drying for three days, the internal substructure was removed and the structure became self-supporting. This important step led to a change in the general structural system. During the treatment the structure was held in place and shaped by the resulting tension from the internal scaffold, generating a tensile structure. However, upon removal of the scaffold the textile structure had to bear its own weight by means of the generated calcified fibrous material, resulting in a compressive structural system.

In this respect, changes as a result of the treatment occurred on three scales of the material.

On a nano scale, the bacteria within the textile material generated a (re)active microbiome, which led to the deposition of microbiologically generated calcite on a micro scale. This, in turn, altered the global behaviour of the structure on a macro scale from a tensile to a compressive structural system. These complex and interdependent processes on different scales together form a biologically active multi-scalar textile-based composite material (Figure 222 - Figure 224).

Figure 220 Substrate before treatement

Figure 221 Substrate after treatment

→

Figure 222 SEM microscopy 350 X mag. (University of Angers)
Figure 223 SEM microscopy 1000 X mag. (University of Angers)

Figure 224 SEM microscopy 1300 X mag. (University of Angers)
Figure 225 SEM microscopy 6000 X mag. (University of Angers)

SEM microscopy 350x magnification, column sample

(Image redacted for copyright reasons)

SEM microscopy 1000x magnification, column sample

(Image redacted for copyright reasons)

SEM microscopy 1300x magnification, column sample

(Image redacted for copyright reasons)

SEM microscopy 6000x magnification, column sample

(Image redacted for copyright reasons)

6.3.3. Discussion

The experiment was able to successfully prove that an active textile microbiome is capable of triggering a calcification process on a micro level, altering the global structural behaviour and transforming a tensile textile structural system into a load-bearing structure. The following section examines the project in relation to the initially identified objectives.

1. Metabolism

The calcification is triggered by a by-product of metabolic ureolysis of *S.pasteurii* (Zhu & Dittrich 2016). This reaction happens on a nano level and triggers calcite precipitation, which gradually solidifies the textile substrate. Here, the textile microbiome reacts to external chemical stimuli of the calcifying solution. Compared to an autopoietic system, this metabolic reaction is time based, and occurs over a period of approximately six hours and doesn't involve cellular self-replication.

2. Global geometry and topology

The textile system applied two optimisation strategies. First, the topology (diameter) of the substrate yarn changes according to the expected load case. The variation in the diameter enabled targeted material deposition (more material at the base, less towards the top). Maintaining the analogy with the tree, this would be coherent with the relative thickness of the branches compared to the trunk.

A geometrical optimisation could be realised through the locally defined knitting patterns. In this case, the material deposition and structural system could be controlled through the change of patterns, which would be equivalent to the distinct morphology and geometry of the branches of a tree.

3. Structural gradient on a micro scale

A gradual transformation from soft to rigid could be demonstrated over the treatment period, dependent on the bacterially induced material deposition on a micro scale (see SEM images). Although it was not able to fully control and test the idea of a local material gradient on a micro scale, the gradual deposition after each treatment cycle potentially offers the opportunity for a local microstructural variance (see treatment below).

4. Fibrous structural strategy

The textile microbiome-induced calcification, similar to the lignin deposition during the growth of a tree, enabled the gradual solidification of a predetermined fibrous scaffold by establishing a structural matrix.

Figure 226 Self-supporting structure after treatment →

A tree expands by depositing new material on its outer perimeter, which is equivalent to a layering strategy, and is always dependent on its immediate substructure. The calcite deposition works similarly, on the outside of the individual fibres; however, the spatial arrangement of the textile increases the surface area significantly. Calcite can be deposited simultaneously across the whole structure; hence a structural change can happen in a short time.

The technical system, including the liquid management and irrigation system, as well as the rotating structure, worked reliably throughout the period of the experiment. The installation performed overall reliably and produced the anticipated result. However, during the process various potential opportunities for improvement and future developments could be identified.

1. Material

The material deployed (jute) was proven to respond well to the treatment, generating a rigid calcite-bound composite. However, there is still space for improvement in relation to its behaviour. A closer investigation into the composition, quality and density of the fibre is needed to optimise the material, thus increasing the material consumption and reducing the overall weight while improving its structural performance.

For the experiment, the thread thickness was determined by the maximum thickness which could be used with the loom that was designed and the knitting patterns deployed. The reasoning for aiming for the maximum thickness was to incorporate additional structural redundancy. Further material testing could feed into a more precise simulation, which could also contribute to further optimisation processes.

2. Setup

The setup for the project was tailor-made to fit the specific shape of the sample. Therefore, the bioreactor has limited capacity for housing any shape of sample; however, the setup provides some flexibility, as other structures which fit within the confined space could potentially be treated in the same way.

3. Treatment

The irrigation treatment enabled enhanced efficiency in comparison with the submersion method in relation to the ratio between liquid use and sample size. It uses less liquid for treating larger samples while reusing unused liquid by reintroducing it to the irrigation cycle. During the experiment the system performed constant irrigation homogeneously, spreading the liquid over the specimen (Figure 227). This process activated the structure uniformly, as all the sprinklers were set to the same flow-rate and connected to one hose. In order to further explore

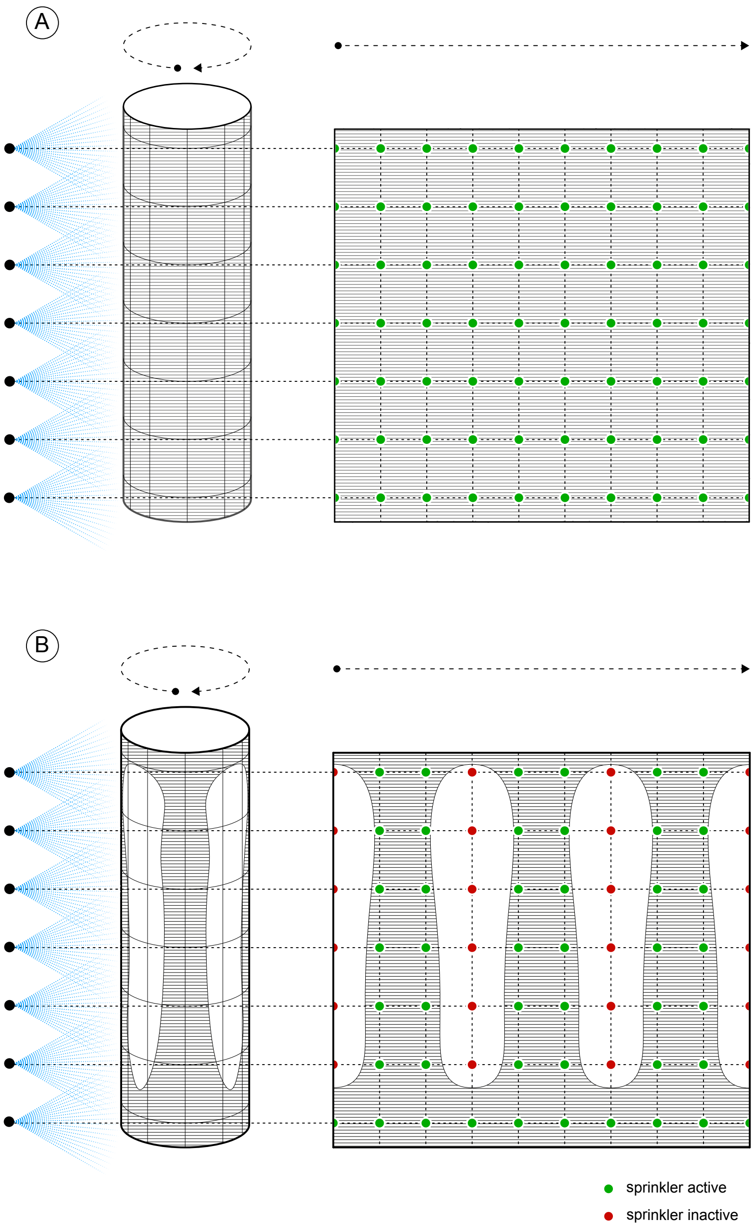


Figure 227 CNC treatment scheme

Figure 228 treatment cycle 2, calcite deposition

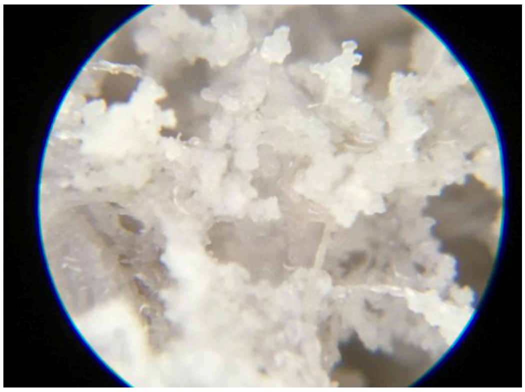


Figure 229 treatment cycle 6, calcite deposition the idea of a graded and optimised material system, an array of separately selectable and adjustable sprinklers, which could be driven through a CAD/CAM framework, would enable the calcification to be triggered locally within the structure. Such a scenario could consist of a pre-treatment topological optimisation process, which determines the exact treatment pattern, generating rigid areas as well as soft areas within one material system, solely by the means of bacterial activity (Figure 227).

4. Efficiency

As there is no precedence for the bacterial treatment of a medium-scale textile structure, the process relied for the most part on experiences from previous small-scale experiments, as well as the expert knowledge of the laboratory technician on site.

Due to the lack of laboratory test equipment on site to observe the activity of the bacteria, which would indicate how reactive the bacteria are (however not whether a thorough calcification had occurred within the material), the experiment relied extensively on experiential knowledge. Furthermore, the short time-frame and the off-lab conditions led to the decision to increase the quantitiy of bacterial and calcifying liquids in order to create more redundancy.

These measures accounted for a probably over-extensive use of water, bacteria, and chemicals. Further tests could provide useful data to make this process more efficient.

7. More than a duck, not quite a tree

7.1. Contribution to knowledge

Through the series of études, demonstrators and scenarios outlined in the previous chapters, the research has aimed to investigate the field of composite materials within the architectural domain through the lens of biological metabolism. The practical tests involving materials, processes and design strategies contribute to the extension of the material repertoire of materials for architecture and design.[27]

Throughout the research, the interdisciplinary methods not only resulted in synergies but also caused friction and debate, and challenged both the researcher's and collaborators' preconceptions. Although these processes are not directly perceptible in the outcomes, they shaped the projects as much as the tools and materials which were used to make them. In particular, in the context of collaborative work, to untangle an individual participant's contribution to a project can be challenging, if not impossible. The synergy of a (true) collaboration harnesses the collective and emergent intelligence and skillsets of a group, creating a dynamic exchange of ideas channelled into one outcome. A retrospective taxonomy bears the danger of painting a reductionistic and overly simplified picture of the processes in which the multifaceted collective workflow can appear to lose its finesse. With this in mind, the following paragraph aims to comprehensively outline the main contributions to knowledge which the project claims to have achieved with the individual projects.

Theory

The theoretical section aims to set the stage for the practical work and similarly contribute to the generation of new knowledge by:

1. Establishing a theoretical contextualisation of the Turm 2 project (Beyer 2015) with the notion of biological metabolism and autopoiesis. (Chapter 4)

2. Reframing the notion and function of a textile microbiome and its utilisation for fibrous composite materials and metabolising matrices;

3. Outlining potential production processes for textile substrates with a dormant textile microbiome. (Appendix G)

27 the column project was presented at several conferences and was well perceived in the architectural research community (for more information see Appendix K)

Practice

The main objective was to investigate the practical implications of an active textile microbiome, on a material as well as an infrastructural level, within a design context. It could be demonstrated that a targeted microbiological colonisation of a fibrous material can generate materials which react to external stimuli. Concomitantly, the distinct agency of a textile microbiome generated a multi-hierarchical composite. This was expressed through the build-up of a subordinate micro structure within the medium, generated by the distinct metabolism of the applied microorganisms. The microstructures, in turn, influenced the structural behaviour of the medium in relation to the emerging properties, resulting from a combination with the fibrous substrate. During the experiments three different microorganisms (*P. Ostreatus*, *A. Xylinum*, *S. Pasteurii*) were employed, which could be triggered to generate three different by-products (chitin fibre, nano-cellulose, calcite). The local and global behaviour of a textile material could therefore be influcenced by means of biological metabolism. The following section dissects the individual approaches and their contribution.

1. Etude 1

Application of a winding method to an active mycelium-based composite material. Based on projects such as Mycelium Tectonics (Tabellini 2015), the project applied a winding pattern derived from the Turm 2 project to a mycelium-based material.

2. Etude 2

Incubation of an *Acetobacter xylinum*-based textile microbiome on directional natural fibres on a surface culture, a system based on a rotary setup (Islam et al. 2017) and an aerosol (Hornung et al. 2007) culture. Although the investigations have not been studied in a large-scale proof of concept, the rotary system and the aerosol system in particular illustrate potential strategies for the incubation of larger-scale modules.

3. Etude 3

Establishing a Sporaosarcina pasteurii-based textile microbiome utilising the Biocalcis protocol (Esnault Filet et al. 2012) and triggering a bio-calcification process. Structural testing (compressive, tensile) of jute-based bio-calcified composites in four different fibre layouts.

4. Demonstrator 2: Column

A. Process design 1: Design and demonstration of a novel biocalcification process based on a controlled irrigation system and rotation of the specimen.

B. Process design 2: Design and demonstration of a scaled-up version of the irrigation-based process.

C. Process design 3: Design and manufacturing of a demonstrator system incorporating a base structure, bioreactor and loom (loom design in collaboration with Daniel Suarez).

D. Conceptualisation of a manufacturing process for a graded jute material through a controlled weaving process. Manufacturing of 450m of continuous material with four distinct material gradients (manufacturing by Eurecat Spain)

E. Application of a Sporaosarcina pasteurii-based textile microbiome to a large-scale textile structure with the system developed, and successfully triggering a bio-calcification process through the Biocalcis protocol (Esnault Filet et al. 2012).

7.2. Future trajectory

The research presents a series of metabolism-informed material studies through a variety of études, artefacts and demonstrators. The deliberate choice to work with artefacts and demonstrators instead of prototypes as a research outcome was motivated by the intention to illustrate and focus on the processual, holistic and interdependent character of (proto-) architectural materials. At this stage these artefacts are not understood as prototypes for a distinct use case or application-ready building materials. The freedom of not having a predetermined use-case, regulatory restrictions or mass-manufacturing guidelines allowed for the projects to stand for themselves as individual research artefacts, which embody the result of an interdisciplinary exchange of contemporary technology, biology, architecture and material design. Future research presents the opportunity to extract individual research trajectories based on findings of the study which could focus on case studies with prototypic character for specific use cases.

The research aimed to reframe the function of the textile microbiome in the context of material design while extending the range and understanding of performativity for textile-based composites. As previously outlined, the field of textile-based composites is situated mainly within the engineering discipline, where characteristics such as structural properties or durability are the main factors for their application. Architectural materials, however, are generally embedded in a more complex context which extends, besides structural properties, to qualitative, adaptive and interactive performativity.

Although, the projects described in the research do include, as a starting point, an investigation into the structural properties of the materials that have been generated: the aim throughout the project was to address their active and generative agency within their environment. This also entails the ephemeral and transformational qualities of living systems which challenge the conventional notion of materials as passive entities. Living systems, as shown in the study, can display many different states: biologically active, passive or dormant.

Dependent on these states the relationship of organisms with their environment is reciprocally informed. Such complex biological behaviour offers a multifaceted field for further study, and shift our understanding of architectural materials as mere passive surfaces to a consideration of them as biologically active interfaces.

The future development of this project is dependent and informed (amongst others) by three main disciplines – Biology, Textiles and Computation- which present the main pillars for advancing this research.

1. Biology

The tools and understanding of biology are constantly evolving, offering new opportunities to engage with living systems from a generative as well as observational position. Especially the field of Synthetic Biology which can be considered as a main future driver for bio-technological innovation. Synthetic Biology allows the design of the functional layer and the metabolic pathways of living organisms to a certain extent. This technology is already widely applied in the food and pharmacological industries and is gradually permeating more and more disciplines. Utilizing this technology for material design however is a relatively novel trajectory which potentially allows for customizable bacterial by-products and new potentials for biological reactive and adaptive systems.

2. Textiles

Textiles draw on a rich history within architectural design and present increasing opportunities with the advancing understanding of fibrous materials and manufacturing techniques.

Other fields in which the research into textile materials play an important role can be harnessed in this context.

The medical field for example offers a rich source of knowledge in regards to the interface between biological and fibrous systems. Biocompatible fibres can provide scaffolds for cell-based cultures whereas antiseptic textiles provide sterile materials for wound dressings or bandages. Whereas the presented research focused on a holistic colonisation of a fibrous substrate such technologies would allow for a differentiated and local colonisation hence provide the foundation for graded material systems. Transferring parts of this knowledge from the medical field into the architectural domain might offer new possibilities and perspectives on composite materials.

Furthermore, the field of fibrous composites is constantly evolving. The project can similarly draw from these developments in regards to, for example, automated or robotic fabrication methods and new fibre technologies for structural composites.

3. Computation

The increasing importance of computation in the fields of architecture and biotechnology offer a unique point in history for congruences and interfaces between DNA and binary code. Whereas numerical computation offers simulation and design tools, biological computation allows for the processing and response to distinct information through biological means. The disciplinary overlap between architecture and biology presents a field where an integrated design-pipeline for numerical, as well as biological computation, could foster new opportunities for more efficient, sustainable and adaptive material systems.

Outlook

In regards to the future trajectory of the project, the concept of microstructural gradients and textile-based biomes offers a novel and underexplored field of study.

Cruz & Beckett (2016) specifically allude to the importance of surface morphology and porosity for bio-receptive design. The column project demonstrated that the micro structures of the bacterially generated materials display porous microstructures. This microstructural property could facilitate a secondary colonisation by other organisms. Cruz & Beckett (2016) demonstrated a permanent and self-sustained colonization of cryptogams on engineered concrete elements which established a bioactive surface responding to environmental conditions.

The column project showed that microstructural porosity as investigated by Cruz & Beckett (2016) with engineered concrete can also be established through biological activity. Combining the two approaches- a structural substrate generated through microbiological activity as substitute for the concrete based substrate (as demonstrated with the column project) and a secondary colonisation (Cruz & Beckett 2016) would result in a complex and biologically interdependent material system.

In such a scenario the choreography of the activity for each microorganism culture is essential. Whereas the activity of an S. pasteurii colony while structurally influencing a substrate is very immediate, and its activity decreases rapidly, cryptogams (in the case of Cruz & Beckett 2016) offer a long-term and self-sustained bio-activity; however, cannot induce a significant structural transformation. Combined, they would form a material system which provides both: a bio-derived structure as well as permanent biological activity. A material system such as this, in which each microorganism performs an individual task, could be understood as a synergetic bio-composite.

In order to test such a system, a material sample which was extracted from the column demonstrator is currently undergoing a trial as a potential material for a coral reef remediation programme initiated by TBA21 (Thyssen-Bornemisza Art) in collaboration with Superflex and KWY. In this context the material's receptivity towards the colonisation of maritime flora, as well as micro and macro-organisms, is being investigated. For this trial the samples were mounted on an existing reef in the archipelago of Tonga and will be investigated over a period of several months.

A further increase the biological responsiveness, and possibly even establishing a reciprocal relationship between two or more individual colonies, could result in a symbiotic bio-composite. The field of microbiology offers a wide range of well-researched organisms which have not generally been considered for application in the field of material design.

An extended taxonomy of more diverse textile microbiomes – especially the interaction between fibrous substrate and biological systems – would hereby provide further insight and new combinatory possibilities.

The bigger picture

We have to acknowledge that the resources our modern society currently depend on are limited. At the same time pollution and waste intensive production is part of architectural construction which contributes heavily to the global pollution problems. New materials alone cannot solve the problem holistically, albeit as a crucial part of the puzzle. The material studies presented in this study are still in a preliminary development state but provide a methodological framework for future projects to draw on.

The central elements here are material efficiency through design via multi-hierarchical and inter-scalar geometrical, topological and microstructural optimisation processes. Concomitantly to draw knowledge from the processual character of biology in regards to its material strategies and adaptability. This adaptability can be harnessed through embedding biological agency within architectural material systems.

Even though this research is centred around material changes at a microscale, they could potentially offer a significant contribution when applied at scale. The project tried to make a case for the possibilities and design potentials of materials at the interfaces between manmade and biological material systems. Such material systems render a complex and interdependent relationship between designer and material. The designer as well as the bio-active material possess a distinct design agency which is negotiated and embodied within the final material.

Learning from and harnessing the intrinsic ingenuity of nature's material systems has informed architectural construction throughout history. Modern science hereby offers new tools and methods to advance this relationship. Therefore, it is imperative that architects and designers engage in an interdisciplinary exchange. Such a process asks for the architect to embrace the generalist character of architecture while managing the right depth of engagement with each discipline. As opposed to conventional scientific enquiry which is based on constantly deepening the understanding of a discipline this approach demands to embrace and mediate the breadth and interconnectivity between distinct fields.

7.3. Epilogue

The scope of the research has allowed only a rather narrow spectrum of the vivid shared history between biology and construction to be presented. I decided to take Vaucanson's *Canard Digérateur*, the unintended mascot of the Enlightenment movement, as a starting point, as it stands as the earliest example of a highly elaborate mechanical automaton combined with a very distinctive interpretation of biological metabolism.

Although I would not expect my work to be judged on the same artistic stage, the idea of an automaton informed by the principles of metabolism seemed intriguing in the context of architecture. The duck provided me with a starting point and a mechanical reference point, although the other end of the spectrum had yet to be defined. The biological paragon was found in a tree, literally a living, adaptive and responsive metabolising composite material. However, although these two entities stem from completely different domains, they contoured a conceptual framework. They became a starting point for me to orient myself and negotiate my position and ideas somewhere in between.

Working with living nature as a reference, one continually has to embrace and anticipate the possibility of underachievement. Consequently, a certain degree of clumsiness inevitably characterises the direct comparisons drawn with living nature, and vague metaphors and analogies can sometimes appear rather contrived.

I'm wondering whether Vaucanson really believed, as is often alleged by his historians, that he could generate artificial life by mechanical means, or whether the mechanical means were more a vehicle to inform his conception of life. I, for myself am very grateful that the engagement with biology led me to this approach. This research clearly changed my perspective on, and conception of, life. The work with living organisms, in particular, requires the abandonment of conventional material concepts and the embrace of a true collaboration or negotiation which often, similar to collaborating with humans, involves a confrontation between two living entities.

In this sense, I hope my work to some degree transcends the formal biological analogy of Vaucanson's duck[28] and makes a valuable contribution to the discourse. What I can say with certainty is that my work has not quite reached the complexity of my biological benchmark – the tree – leaving me somewhere between the duck and the tree.

28 This obviously concerns the conceptual biological analogy, and not its mechanical or artistic quality, or its craftsmanship, which I hold in highest regard.

Appendix

Appendix A: ArcInTex: structure and curriculum

The ArcInTex project is part of Marie Sklodowska-Curie Actions (MSCA) which "encourages collaboration and sharing of ideas between different industrial sectors and research disciplines" (Marie Skłodowska-Curie Actions 2018). The MSCA's main areas of engagement are the formal, natural and social sciences, whereas design- or art-related research marks a novel appendix of the institution. The ArcInTex European Training Network (ETN) thus forms the forefront of a multi-national and interdisciplinary art and design research project within the MSCA. The project aims to foster the synergies between the fields of architecture, interaction design and textiles.

At the core of the project, the fields of architecture, interaction and textile design stand as the main pillars from which an investigation into the development of novel textile-related applications and methods depart. As a pilot project its focus lies not merely on material and design innovation but also on field-testing an interdisciplinary research environment and cross-border knowledge exchange between the institutional and industrial partners. The central element is to investigate and reflect upon the notion of the project's lead motif, how to design for "new forms of living and a more sustainable way of life". This is approached through the lens of the three main disciplines (architecture, interaction design and textile design) and the overarching paradigm of "textile thinking". The objective is to locate overlaps and friction, as well as synergies, between different fields to harness new drivers for innovative design processes. A differentiation between work packages is made through the engagement with different scales.

This starts from the scale of the human body and the field of fashion, moving to interior design, and ultimately concluding with the built environment. The field of interaction design can hereby be understood as a mediating discipline between the different scales, investigating the correlation between the human as an actor and her/his impact and relation to their (designed) environment.

Although this scalar distinction was set through the project's agenda, textiles, especially in the context of architecture, demand a multi-hierarchical approach, starting at fibre level and moving through yarn geometry up to the scale of architecture. Ultimately, a reciprocal dependency connects the different scales and informs their behaviour, geometry and characteristics. This correlation will be extensively evident throughout the thesis.

The three-year curriculum was designed to encourage interdisciplinary exchange through a very dynamic setup. A relocation to a different country was obligatory at the beginning of the project, as well as two secondments in different partner institutions in the first two years, each with a duration of six months.

A team of 15 researchers was divided into three work packages (architecture, interaction design and textile/fashion design) according to their focus of study. Each Early Stage Researcher (ESR) worked on their individual project and research topic; however, during the first secondment the ESRs were asked to collaborate on a project. The 5 ESRs of Work Package 2 (Architecture) relocated collectively to Lithuania to work at the Vilnius Academy of Arts on the collaborative project.

In the following year placements with the industrial partners for another six months were scheduled. In this case an individual agenda had to be developed with the industrial partner for this period from which ideally both partners are able to benefit. In the context of this research project a placement at Heatherwick Studio in London was arranged. This provided an excellent test-bed for the research to be contextualised and framed in a commercially operating and renowned architectural design practice.

Furthermore, over the course of the three years, the researchers and supervisors gathered at changing institutions within the programme for extensive workshops. This unique setup contributed to an understanding of the various approaches towards design research within academia and enabled an extensive network of researchers throughout Europe to be built.

1. Vilnius Academy of Arts, Lithuania (22.07.- 01.12.2016)

During the first month the five ESRs of Work Package 2 (WP2) joined an artist residency at the Nida Art Colony on the Baltic coast of Lithuania. After joining a week-long doctoral school held at the Colony we aimed to develop a collaborative project. Our individual backgrounds and specialisms, which included amongst others research into bio-derived composites, computational design, olfactory studies and fashion, interaction design and research into phase-change materials, were thus both challenging and inspiring for our collaboration. The specific challenge was to mediate between the individual fields of research and the formulation of a overarching topic and project. The aim was to generate outputs which form a consistent collaborative piece of work but could similarly inform the individual studies. The challenge of merging the variety of fields into just one formal and thematic approach was, after thorough reconsideration, avoided by suggesting a methodological approach instead. This approach consisted of a collaborative setting in which every participant prepared an informal workshop centred around their research. Through the format of a workshop we could familiarise ourselves with each other's fields of studies and locate potential overlaps of interests and methods. In a second iteration these overlaps would then be explored with another set of explorations. Rather than focusing on the outcomes of the individual workshops, the project aimed at investigating and mapping processes using interdisciplinary dynamics.

The process of the map as well as the outcomes of the workshops were exhibited on two occasions during the secondments. On 26 September 2016 the first workshop and iteration 1 was shown at the Nida Art Colony Open Studios exhibition. The final iteration, together with a large-scale print of the map (Figure 231) and interactive projections was on display at the Academija Gallery in Vilnius from 28 November to 3 December 2016.

The exhibition in Vilnius was named Wolpertinger, after a mythical Bavarian creature. The creature possesses various parts and organs of other animals which is traditionally achieved through rather grotesque method of taxidermy. The underlying concept, however, is the assemblage of different features of a number of animals in one organism. While in the case of the Wolpertinger this is achieved through an obviously oversimplified and mechanistic approach, it still alludes to the interesting relationship between tool and system (integration). In the illustration chosen for the exhibition poster (Figure 230), a rabbit is depicted with the wings of a falcon. Whereas the rabbit in this case possesses the most important feature (tool) to enable flying, it is still highly unlikely that the animal in the illustration will ever be airborne. The wing (tool) in this context demands a specific physiognomy to be able to function in the intended way. In other words, the tool (wing) has to be integrated into a system (body). Both entities, system and tool, can be seen separately; however, their design as well as functionality is only realised through a reciprocal interconnection.

For our interdisciplinary explorations the Wolpertinger stood as a mascot and a metaphoric model to investigate in an interdisciplinary context. For us, the relevant questions deducted from that model was, for example, to which extent tools and methods can be implemented and transferred between disciplines, and whether therefore this established interdisciplinary chimera is able to function as a novel research trajectory.

Figure 230 Exhibition poster

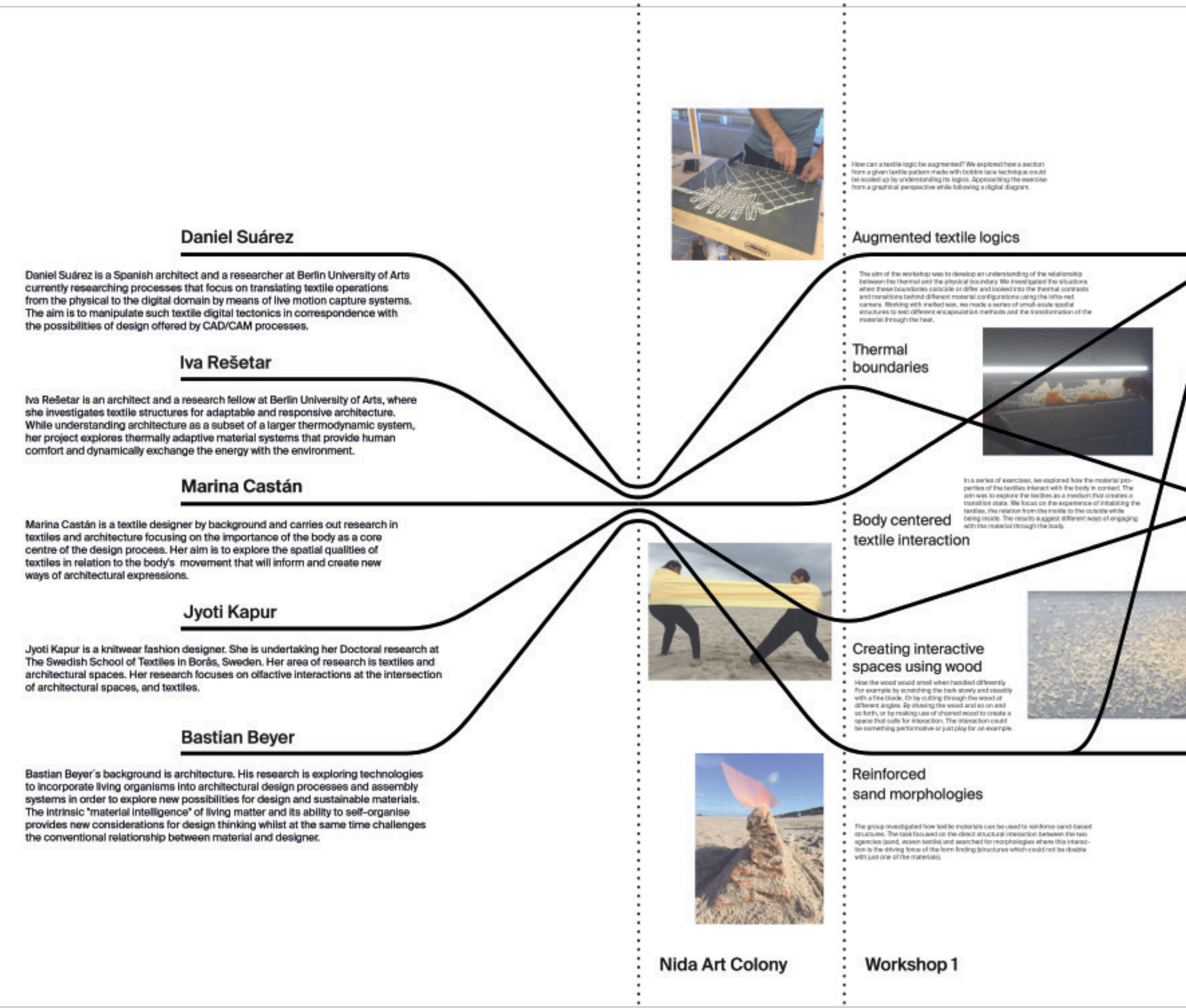
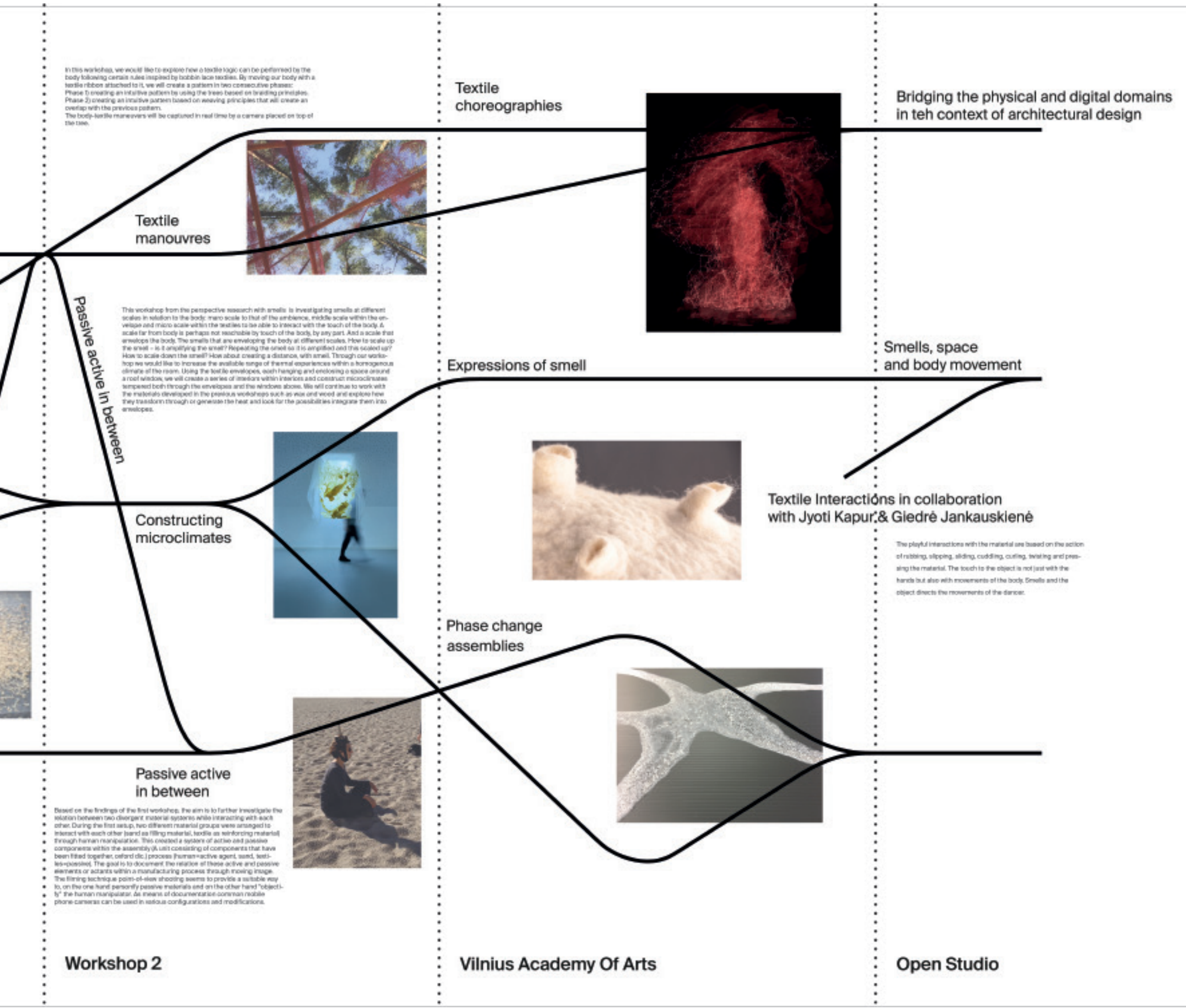


Figure 231 Collaborative map


In this workshop, we would like to explore how a textile logic can be performed by the body following certain rules inspired by bobbin lace textiles. By moving our body with a textile ribbon attached to it, we will create a pattern in two consecutive phases:
Phase 1) creating an intuitive pattern by using the trees based on braiding principles.
Phase 2) creating an intuitive pattern based on weaving principles that will create an overlap with the previous pattern.
The body-textile maneuvers will be captured in real time by a camera placed on top of the tree.
Textile choreographies
Bridging the physical and digital domains in teh context of architectural design
Textile manouvres
Passive active in between
This workshop from the perspective research with smells is investigating smells at different scales in relation to the body: maro scale to that of the ambience, middle scale within the envelope and micro scale within the textiles to be able to interact with the touch of the body. A scale far from body is perhaps not reachable by touch of the body, by any part. And a scale that envelops the body. The smells that are enveloping the body at different scales. How to scale up the smell – is it amplifying the smell? Repeating the smell so it is amplified and this scaled up? How to scale down the smell? How about creating a distance, with smell. Through our workshop we would like to increase the available range of thermal experiences within a homogenous climate of the room. Using the textile envelopes, each hanging and enclosing a space around a roof window, we will create a series of interiors within interiors and construct microclimates tempered both through the envelopes and the windows above. We will continue to work with the materials developed in the previous workshops such as wax and wood and explore how they transform through or generate the heat and look for the possibilities integrate them into envelopes.
Expressions of smell
Smells, space and body movement
Constructing microclimates
Textile Interactions in collaboration with Jyoti Kapur & Giedrė Jankauskienė
The playful interactions with the material are based on the action of rubbing, slipping, sliding, cuddling, curling, twisting and pressing the material. The touch to the object is not just with the hands but also with movements of the body. Smells and the object directs the movements of the dancer.
Phase change assemblies
Passive active in between
Based on the findings of the first workshop, the aim is to further investigate the relation between two divergent material systems while interacting with each other. During the first setup, two different material groups were arranged to interact with each other (sand as filling material, textile as reinforcing material) through human manipulation. This created a system of active and passive components within the assembly (A unit consisting of components that have been fitted together, oxford dic.) process (human=active agent, sand, textiles=passive). The goal is to document the relation of these active and passive elements or actants within a manufacturing process through moving image. The filming technique point-of-view shooting seems to provide a suitable way to, on the one hand personify passive materials and on the other hand "objectify" the human manipulator. As means of documentation common mobile phone cameras can be used in various configurations and modifications.
Workshop 2
Vilnius Academy Of Arts
Open Studio

2. Studio Heatherwick, London (05.09.-15.12.2017)

During the secondment at Heatherwick Studio (with fellow ArcInTex ESR Marina Castan) we were assigned to the Ras al Akhdar Project ((Figure 232), Figure 233). At the time we joined the design Team, led by Arturo Revilla, the project had just undergone a major design revision, which included a reconsideration of the building volumetric, layout and geometry as well as the façade design. We were engaging in small-scale model building and preparing and joining the reviews with Thomas Heatherwick, as well as assisting with the client submission. Besides being active part of the design team, we were asked to use the project as a speculative framework to implement our individual research topics.

The building site of the project is located on a peninsula in Abu Dhabi, which is mainly comprised of sand. The abundancy of one prevalent material triggered an investigation into how to use sand as a main building material. Focusing on biological binding agents, the field of biocalcification emerged as a potentially valuable strategy. Thus the primary focus was on the design and generation of a non-structural façade and shading elements.

A preliminary study on sand solidification through bio-solidification was realised with support of Soletanche Bachy in Paris. This study investigated surface treatment methods based on distinct patterns which were cut into acrylic sheets. In this way the aim was to generate a morphological representation of the stencil patterns through gradual and local permeation of the bacterial liquid (Figure 234 - Figure 237).

Based on these experiments, a CNC injection method was developed to solidify the sand locally with a higher degree of control. An off-the-shelf 3D printer was modified with a customised injection nozzle (Figure 238 , Figure 239) and controlled via a Rhino/Grasshopper/Silkworm (Parametric model to G-Code) pipeline. While it was not possible to test the developed system with the bacterial solution, the setup delivered a series of morphological studies by using diluted PVA glue (Figure 243 - Figure 247). Furthermore, a speculative in-situ production method using CNC controlled robotic arms was conceived (Figure 248).

Heatherwick Studio has expressed its interest in further investigation into the topic.

Architectural model Ras al Akhdar

https://www.middleeastarchitect.com/portfolio/heatherwick-studio-designs-clustered-boutique-hotel-development-in-abu-dhabi

(Image redacted for copyright reasons)

Figure 232 Ras al Akhdar Project, Heatherwick studio (2018)

Architectural model Ras al Akhdar

https://www.middleeastarchitect.com/portfolio/heatherwick-studio-designs-clustered-boutique-hotel-development-in-abu-dhabi

(Image redacted for copyright reasons)

Figure 233 Ras al Akhdar Project, Heatherwick studio (2018)

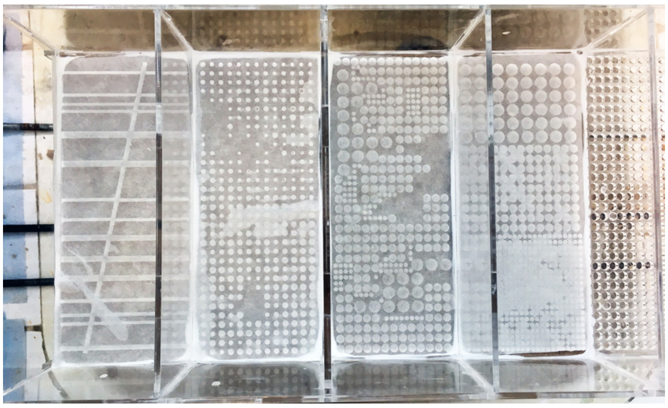


Figure 234 Test setup

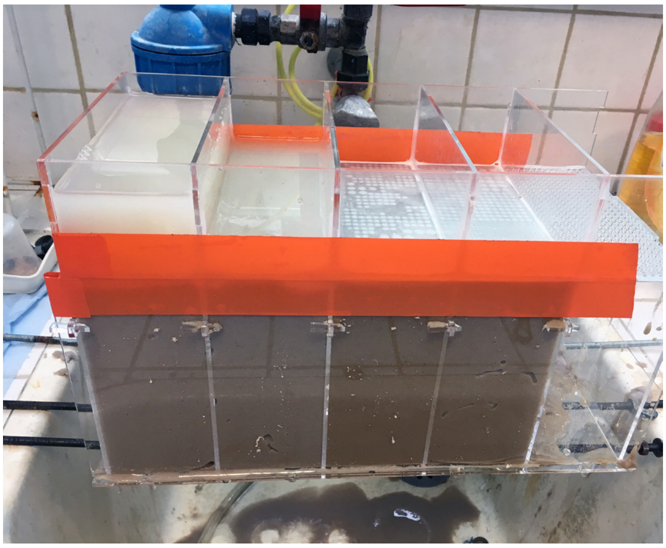


Figure 235 Process; bacterial liquid permeates sand medium

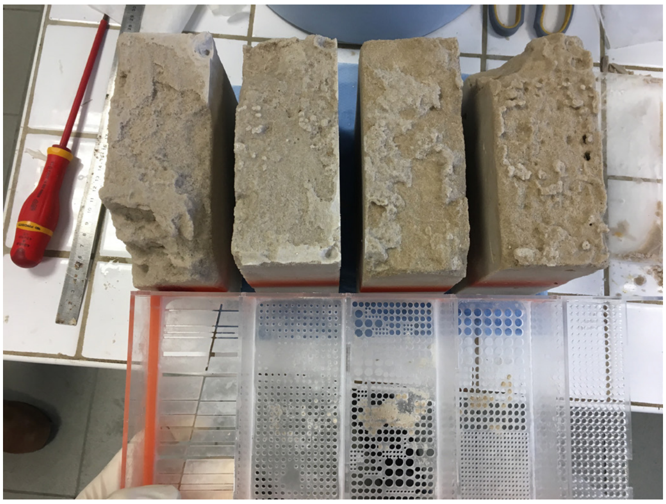


Figure 236 Formwork removal

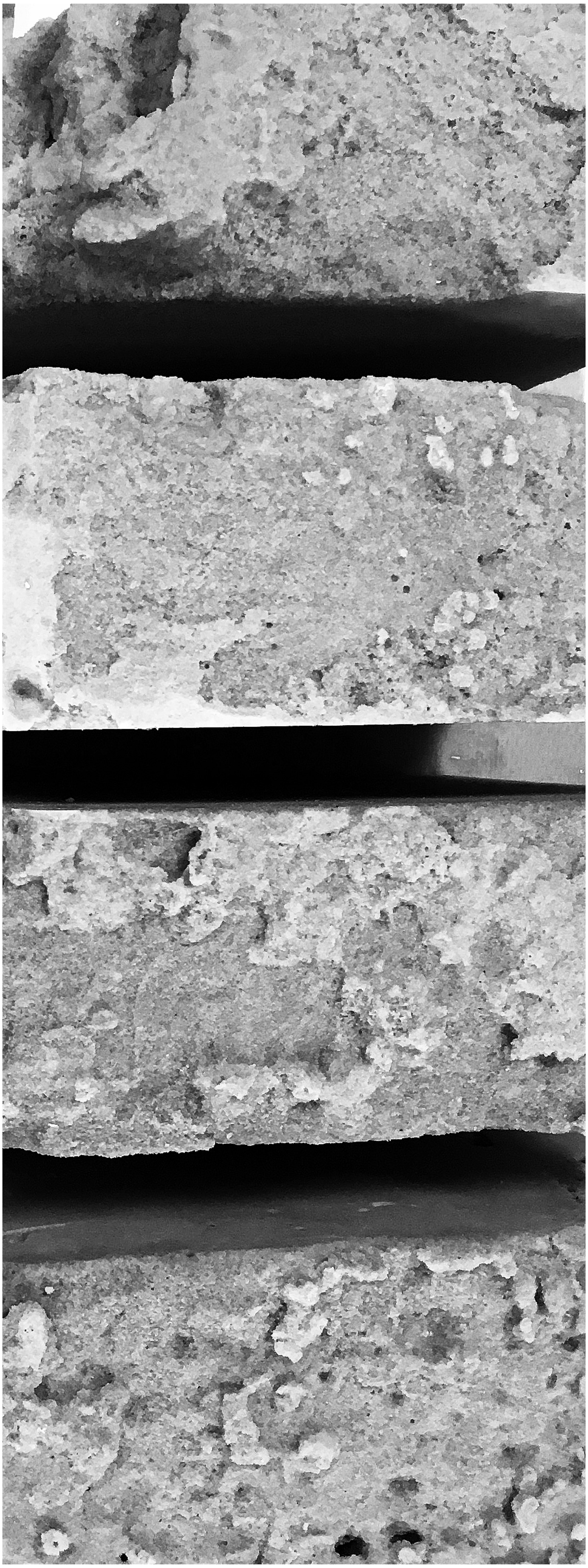


Figure 237 Biocalcified sand morphologies

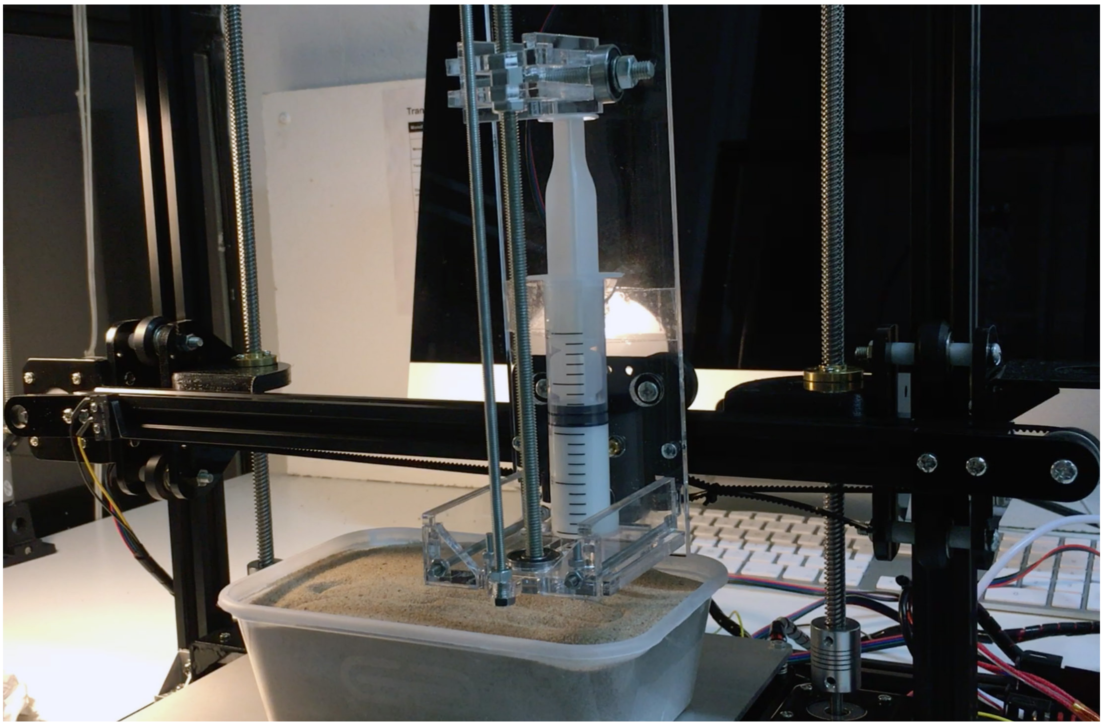


Figure 238 Modified 3D printer

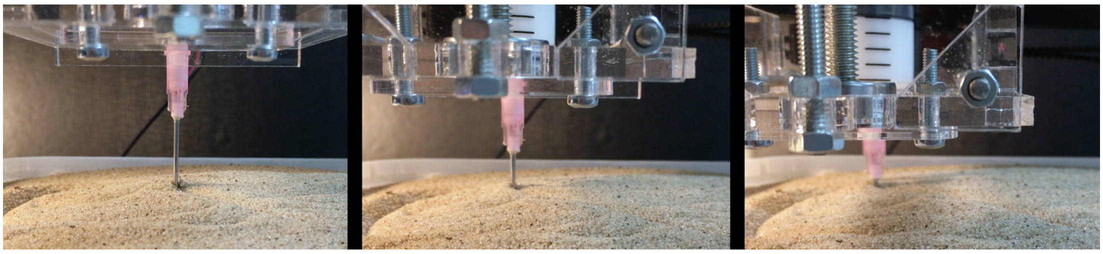


Figure 239 Modified 3D printer; injection nozzle detail

Figure 240 Injection printing process, detail 1

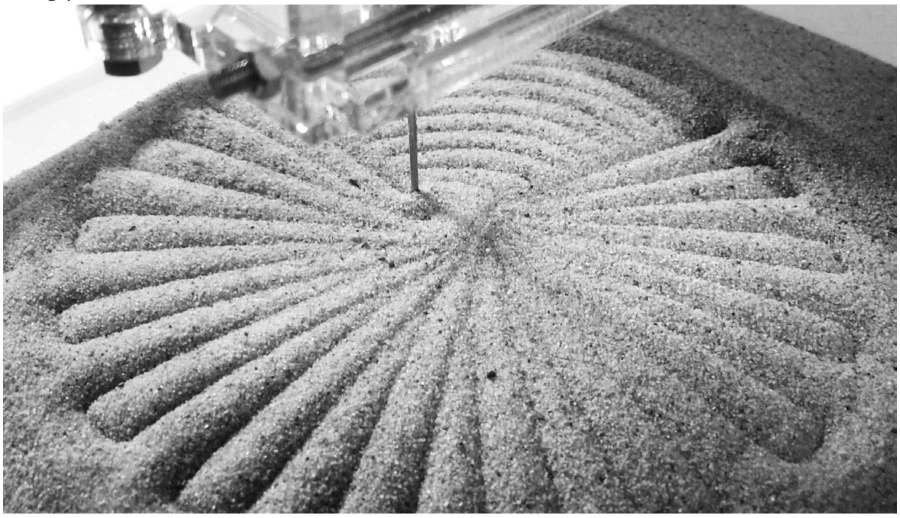


Figure 241 Injection printing process, detail 2

Figure 242 Injection printing process, detail 3

Figure 243 Object extraction; Unsolidified sand removal

Figure 244 Sample 1

Figure 245 Sample 2

Figure 246 Sample 3

Figure 247 Sample 4

Figure 248 On-site manu-facturing scenario

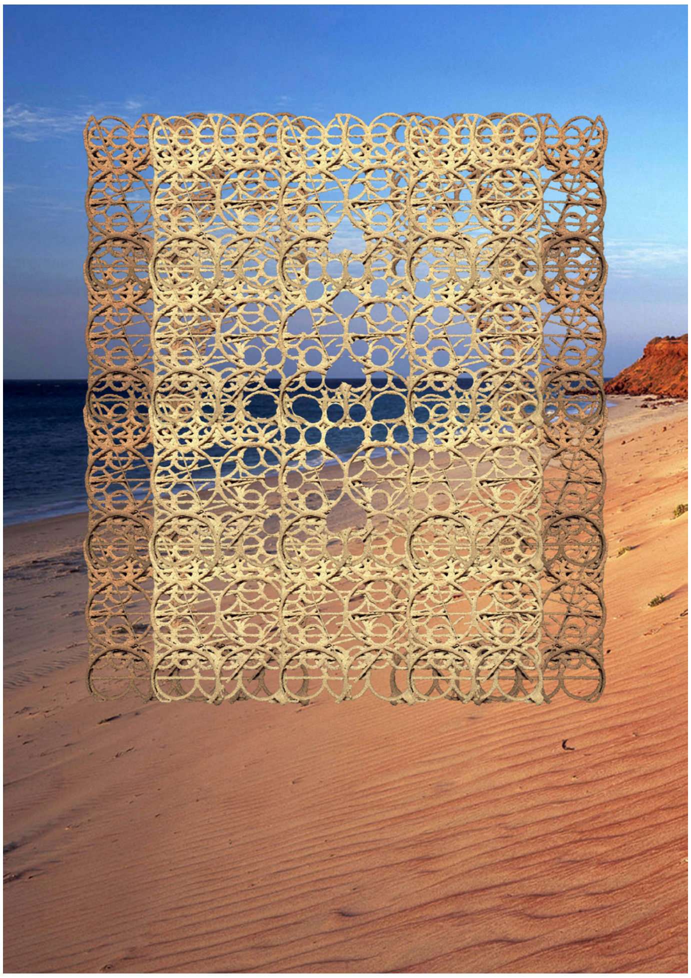


Figure 249 façade study

Appendix B: The transdisciplinary discourse

The following section investigates the notion of transdisciplinarity as a mode of collaboration. The field of cybernetics presents a pivotal point for modern sciences and is used in this context as a case study and example for the emergent interconnectivity of disciplines. The paragraph discusses Norbert Wiener's writings on collaboration from his fundamental work Cybernetics: control and communication in the animal and the machine in the light of the contemporary notion of transdisciplinarity.

> The mathematician need not have the skill to conduct a physiological experiment, but he must have the skill to understand one, to criticize one, and to suggest one. The physiologist need not be able to prove a certain mathematical theorem, but he must be able to grasp its physiological significance and to tell the mathematician for what he should look for. (Wiener 1961, p.3)

Before the various notions of inter-, trans- or multi-disciplinarity had been widely discussed, Norbert Wiener (1961) outlined in the introduction, cited above, to his foundational work (written in 1947) on the new field of science which he later coined cybernetics, a rather humble vision of interdisciplinary collaboration which triggered probably one of the most significant transdisciplinary ventures in science to date. In an era of scientific specialisation Wiener and his colleagues set out on a new research venture between the established sciences. Driven by this spirit of collaboration the emergent field of cybernetics developed. As this new science was gradually established, various fields of science, such as mathematics, physics, medicine, biology and engineering, joined forces to investigate the underlying principles of information and control mechanisms in engineering, as well as biological, systems (Ashby 1961). The concept of cybernetics, such as electromechanical and control and feedback systems, which mark the foundations of modern computer technology, gradually permeated the biological domain, which then posed questions of a higher order, such as the human-machine relationship. This borderless knowledge exchange, combining the implications of the findings across multiple disciplines while forming an individual and distinct genre of research, can be understood as an archetypal result of a transdisciplinary process (Nicolescu 2005, p.4) locates the transdisciplinary concept

> at once between the disciplines, across the different disciplines, and beyond all discipline. Its goal is the understanding of the present world, of which one of the imperatives is the unity of knowledge,

arguing not merely for an exchange and communication between individual disciplines but also for embracing a wider integration into other bodies of knowledge. Bernstein (2015) suggests that current complex or "wicked" problems call for a transdisciplinary approach to “think laterally, imaginatively, and creatively not only about solutions to problems but to the combination of factors that need to be considered”.

Norbert Wiener, who had already engaged with the first conceptualisation of cybernetics by 1948, described in the quotation at the start of this section a rather linear knowledge exchange between experts from different fields, which would be considered an interdisciplinary approach. According to Nicolescu (2014, p.187), an interdisciplinary approach “overflows the disciplines, but its goal still remains within the framework of disciplinary research. Interdisciplinarity (even) has the capacity of generating new disciplines”.

Wiener outlines an approach in which scientists adapt knowledge from an hitherto unfamiliar field sufficiently to be able to engage with it to the degree which enables communication, constructive criticism and collaborative problem solving (Wiener 1961). He argues for these skill sets to be developed by:

> possessing a thoroughly sound and trained acquaintance with the fields of his neighbors; all in the habit of working together, of knowing on another’s intellectual customs, and of recognizing the significance of a colleague’s new suggestion before it has taken on a full formal expression (Wiener 1961, p.3).

Whereas these sets of rules pave the way for a seamless integration of knowledge of different fields, Wiener also hints at a concept of higher significance when he pictures a newly assembled research group of independent scientists

working together in one of these backwoods of science, not as subordinates of some great executive officer, but joined by the desire, indeed by the spiritual necessity to understand the region as a whole and to lend one another the strength of that understanding.

Departing from his technical and discipline-bound terminology, Wiener paints a picture of an adventurous quest to holistically “understand” the “new region” in a condition of “spiritual” synergy and exchange of “strength”. Arguing against existing hierarchical structures (“subordinates”, “great executive officer”), he advocates for a “desire”-driven research. This can be understood literally in the context of organisational structures within a university or business, but can also be construed from a more compelling, disciplinary viewpoint. Disciplines comprise multiple levels of sub-disciplines, generating a branching, tree-like and hierarchical system. The intriguing thought experiment of (geometrically) flattening these structures would allow for non-linear and non-hierarchical networks to emerge, which could potentially assemble into new formations without hierarchical determinism. This would result in new connections between fields which were not possible earlier because of the strict organisational postulate of branching hierarchies. A collapse of these structures would result in a non-hierarchical playground for the sciences.

Besides advocating against the persistent hierarchical structures, Wiener also departs from a strict conception of distinct disciplines, elaborating on the notions of a "region" and the "backwoods of science", suggesting a spatial concept of knowledge and implying the idea of a mediating matrix permeating the prevalent disciplines. Ultimately, the foundational work Wiener contributed to the advancement of the field of cybernetics operates within a highly transdisciplinary context. The origins of the field, in terms of its approach towards disciplines, is based on a shared approach between a transdisciplinary contextualisation of the practice which was informed by (early) interdisciplinary collaborations and problem solving. This approach can be observed in projects such as the development of an apparatus for curvilinear prediction for anti-aircraft artillery. This project led to investigations into feedback mechanisms, which then again, through a broader contextualisation and collaboration with the field of medicine, especially with Dr. Arturo Rosenblueth, that resulted in an investigation into the "fundamental notion of message … transmitted by electrical, mechanical, or nervous means." (Wiener 1961, p.8) Wiener's holistic and anticipatory thinking therefore contributed significantly to the overarching relevance of cybernetics. In this respect, transdisciplinarity can incorporate interdisciplinarity, but interdisciplinarity does not necessarily operate transdisciplinarily.

Transdisciplinarity, in general, does not imply the dissolution of disciplines, nor does it render disciplinary competence obsolete (Mittelstraß 2011). In fact, it is a necessary resource for successfully navigating and working in a transdisciplinary context. Research questions, however, usually emerge from a distinct problem within a discipline, which then might result in interdisciplinary problem solving. Leavy (2011) suggests, contrary to disciplinary-derived research, that "Transdisciplinary research practices are issue- or problem-centered approaches to research that prioritize the problem at the center of research over discipline-specific concerns, theories or methods." (Leavy 2011, p.14)

In this notion the question and its relevance, as well as its impact, are central. The means and toolsets for potential solutions are then acquired and combined from various disciplines and competences. The transdisciplinary approach is distinguished from other modes of collaboration through its deliberate connectivity with other fields of knowledge, embracing the intrinsically complex nature of the sciences.

Traditionally, science operates with a reductionistic model which extracts a problem from its context in order to find one specific answer to one specific question within one specific setting. The objective experimentation empirically delivers exact, reproducible and quantifiable data models which then, in turn, are applied to a context or "reality". This approach informs and shapes our modern "reality". The traditional scientific methods and models shaped the prevailing disciplinary landscape and helped to develop and advance our contemporary sciences (Nicolescu 2014). However, architecture as a discipline is innately linked to context, environment and society. It operates in a highly interrelated context, and therefore a reductionistic model of research cannot fully deliver a suitable answer to a contextualised or complex problem.

Complex systems (or problems) differentiate themselves from complicated problems, for example, through their emergent constitution. The distinct interaction between each of the components (of the system or problem) and their environment results in an effect which cannot be fully understood by the mere interaction between each individual part (Bernstein 2015). Bernstein (2015) suggests that, in this respect, a transdisciplinary approach itself bears emergent potential, as

> information, data, theories, and methodologies from multiple disciplinary viewpoints are brought into the [transdisciplinary research] process and are . . . combined in order to create something new that is irreducible to the disciplinary components that were initially brought to bear (Leavy 2011, p.31)

and could therefore offer one way to approach increasingly complex, multifaceted questions in an era of increasingly converging, interdependent fields of science where "transdisciplinary work challenges the entire framework of disciplinary thinking and seeks to assemble new approaches from scratch, using materials from existing scholarly disciplines for new purposes".(Bernstein 2015)

Appendix C: ITKDE/ICD Pavillions

1. ITKE/ICD Pavilion 2013/14

The 2013/14 ITKE Pavilion (Figure 251) utilised a robotic winding method as a construction technique for modular, textile-based structural elements. The system employs a modular approach which allows for the prefabrication of the elements off site (Figure 250). For the manufacture of the elements, two base plates were mounted on separate collaborative robotic arms, between which resin-impregnated carbon or glass fibre filaments are spun.

The tensing of the fibres between the two base plates accounts for the structural integrity of the individual module, as well as for their global behaviour after the assembly.

A biomimetic design approach informed the project from an early stage. The micro structure of the protective shell structure of the Elytra beetle was analysed, and delivered a role model for an anisotropic fibre structure with a governing anticlastic geometry (Parascho et al. 2015). The anisotropic behaviour was established through the specific winding pattern, as well as the use of a combination of glass and carbon fibres within the module. The material differentiation allows a combination of the properties of the both fibre types.

The project exploits the advantage of the coreless winding technology to fabricate one-off elements with less effort than conventional systems, which demand a complicated mould to be made beforehand onto which the fibres are laid (Knippers & Koslowski 2017). Due to the versatility of robotic arms with regard to their software as well as their hardware, a change of geometry can be implied by simply re-coding the winding process instead of changing the whole machinery.

The composite winding method in general is in principle a very simple and logical manufacturing system derived from manual craftmanship; however, state-of-the-art simulation and manufacturing methods allow additional complexity and precision which outpaces human capacity. This duality generates high-tech textile tectonics with very relatable filamentous aesthetics.

Various iterations of the technology in different architectural contexts (e.g. Elytra Filament Pavilion, V&A 2016, BUGA Pavilion, 2019) show the versatility of the fundamental principle of composite winding.

Robotic coreless winding (ICD/ITKE)

http://www.achimmenges.net/?p=5713

(Image redacted for copyright reasons)

Figure 250 Coreless winding technology (ITKE/ICD)

2013/14 Research Pavillion

https://icd.uni-stuttgart.de/?p=11187

(Image redacted for copyright reasons)

Figure 251 2013/14 ITKE/ICD Research Pavilion

2. ITKE/ICD Pavilion 2016/17

Whereas the 2016/17 ITKE/ICD Pavilion presents a modular approach, with individually wound sub-structures which establishes, once assembled, a load-bearing structure, the following example illustrates the assembly of large-scale truss elements manufactured in one piece.

The resulting structure can be understood as a monocoque structure, which accounts for the structural performance as well as generating an architectural envelope or skin while maintaining a continuous materiality. The concept was also applied in the MIT/Monsanto House of the Future project (Dietz 1965). In the case of the House of the Future the structural performance of the continuous glass-fibre composite accounts for its sandwich structure (composite, foam, composite) and its distinct double-curved geometry, as well as its filleted edges (Dietz 1955; Dietz 1965)(Figure 253). This strategy pairs a global geometrical optimisation with selective material composition. The constitution of the structural composite skin, however, remains constant throughout the structure.

The following project investigates both a geometrical and material optimisation and a customisation of internal geometry and build-up of the composite layering, thus generating a "functionally graded monocoque composite structure" (Solly et al. 2018).

Whereas Semper (Semper 1860) differentiates between structural and textile elements within an architectural system, modern graded composites enable functionally graded materials by accommodating both properties in a continuous materiality (Palz 2012)..

The 2016/17 ICD/ITKE Research Pavilion applies a similar biomimetic strategy, as the previously presented project. Inspired by the morphology of silk fibre structures generated by two species of leaf miner moths, Lyonetia clerkella and Leucoptera erythrinella, whose fibrous structures span relatively long distances (Figure 254), the design process utilises these construction and structural principles to inform a scaled-up system.

The digital design process, similar to the previous project, consisted of an initial form-finding process informed by an in-depth investigation of the natural fibre micro-tectonics generated by the moths (Figure 255). These principles informed the layering system and the fibre morphology. Furthermore, this design underwent structural analysis which optimised its material use and structural performance (Solly et al. 2018)(Figure 256).

Side view pavilion

https://icd.uni-stuttgart.de/?p=18905 Roland halbe

(Image redacted for copyright reasons)

Figure 252 ITKE/ICD Pavilion 2016/17

Construction process House of the Future

https://davelandblog.blogspot.com/2012/05/tpe-monsantos-house-of-future.html

(Image redacted for copyright reasons)

Figure 253 MIT/Monsanto House of the Future composite sandwich module with double curved geometry and edge fillet

In order to continuously fabricate a long-span structure without segmentation, an automated multi-actor fabrication process was developed (Solly et al. 2018). The setup consisted of two robots placed at the end of the structure near the nodal points for fibre winding. As the robots possess a limited working area, the intermediate space was bridged by an autonomous multi-copter (Figure 257). During the fabrication process the filament was wound onto a nodal point at one side of the structure. Subsequently, the filament was passed to the multi-copter and flown to the other side where it was received by the second robotic arm which wound it to the predetermined nodal point on the opposite side of the structure. Gradually the 12m cantilevering fibre structure emerged through winding fibres between the two arrays of boundary winding points on each end.

Moth fibre structure

https://icd.uni-stuttgart.de/?p=18905
picture 2 (development process)

(Image redacted for copyright reasons)

Figure 254 Fibre structures generated by the leaf miner moths Lyonetia clerkella and Leucoptera erythrinella

Moth fibre structure , microscopy

https://icd.uni-stuttgart.de/?p=18905
picture 5 (development process)

(Image redacted for copyright reasons)

Figure 255 Fibre microstructure

Moth fibre structure

https://icd.uni-stuttgart.de/?p=18905 picture 12 (development process)

(Image redacted for copyright reasons)

Figure 256 Robotic manufacturing setup, workspace of robots extended through employing a collaborative multi-copter

Moth fibre structure

https://icd.uni-stuttgart.de/?p=18905 picture 8 (development process)

(Image redacted for copyright reasons)

Figure 257 Multi-actor fabrication process and composite structure

Reflections on the case studies

Advances in composite materials are largely dependent on innovation in three main fields: fibres, matrix materials and manufacturing methods. These fields originated as three distinct disciplines within the field of manufacturing and material research, and are still operating as independent entities in the technical textile and polymer industries, as well as in robotics and automation technology. The field of composites bridges these fields, and thus profits from developments in each individual discipline.

The case studies illustrate how fibre-based composites can be manufactured for complex performance, such as directional, isotropic or anisotropic behaviour. The process of their manufacture can directly be embedded into the design process to foster these advantages for unique structural solutions.

The distinct textile tectonics and complex structures are fostered through a relatively simple principle which is based on the emergent behaviour of individual fibres in a specific array and direction, embedded in a rigid matrix. By pairing this principle with state-of-the-art manufacturing and design methods, novel aesthetics emerge.

The distinct feature of textile-based composites is their material transition, which allows for a soft manufacturing during which the individual fibres behave in a textile-like way. During this stage the manufacture of composite winding techniques is based on a tensile system. In the specific fabrication processes outlined in the case studies, the robotic winding establishes a tensile system through the winding of individual fibres between the nodes. During the curing process their state changes from one that is soft and mouldable to a rigid system with global behaviour which can, besides tensile forces, withstand compressive forces.

Case Studies 1and 2 illustrate impressively the potential of integrated composite manufacturing for the architectural domain. The high-tech materials deployed for the project consist of carbon and glass fibre impregnated with high-performance resins. While they deliver unprecedented performance in relation to their structural property, light weight and durability, their production demands large amounts of energy and is heavily dependent on petrochemical resources (Netravali & Pastore 2014). Additionally, there are major challenges in terms of their recycling (US Department of Energy 2015). Alternatives, in the form of sustainable composites, thus offer potential solutions to these drawbacks.

Appendix D: Sustainability of composites

The major drawback of the majority of polymer-based composites is their dependency on petrochemical technology and resources, as well as their energy-intensive production methods (Netravali & Pastore 2014). The energy needed for a carbon-fibre composite element is estimated to be three to five times higher than an component of the same weight manufactured in steel (US Department of Energy 2015).

The use of high-performance and highly energy-intensive composites legitimises their application within the automotive industry, and particularly in the aerospace industry, where the specific weight of a structure relates directly to fuel consumption and efficiency: the primary energy investment in the component can thus be amortised over the period of use. In contrast to the aviation industry, the weight factor in the field of architecture is of relatively low significance. Therefore, the significant embodied energy of a lightweight component is generally not amortised during its lifespan.

Another current drawback is the limited recyclability of glass fibre- and carbon fibre-based composites. Current resin technology is based on an irreversible polymerisation process of binding the fibrous materials within a rigid polymer matrix. This system poses a challenge to a recycling strategy which aims for the separation of individual constituents of the composite for reuse. There are three main strategies that are currently explored to recover raw materials from decommissioned parts, consisting of a decomposition of the composite by mechanical, chemical or thermal/pyrolytic means (Witik et al. 2013; Oliveux et al. 2015). Although these strategies are able to recover the fibrous constituent of the material in an energy-intensive and pollutive process, the resulting quality of the fibres decreases significantly, which inhibits

Carbon fibre sheets

https://www.firgellirobots.com/products/rigid-3k-carbon-fibre-sheet-plain-weaving

(Image redacted for copyright reasons)

Figure 258 Carbon fibre panels, directional, continuous weave structure

Chopped Carbon fibre

https://www.indiamart.com/proddetail/carbon-fiber-chopped-strand-9434027430.html

(Image redacted for copyright reasons)

Figure 259 Discontinuous, uni-directional carbon fibre after the recycling process their full reuse. This means that the components currently have to be shredded to undergo the processes, so the formerly continuous fibres can only be recovered as short or milled fibre material, and therefore lose their initial high-performance properties (Figure 259). The matrix material is either dissolved during the chemical process or burnt through pyrolysis, so it cannot be recovered (US Department of Energy 2015).

A reuse of the recovered raw materials to produce composites of the same quality is therefore currently not feasible, due to the degradation of the raw materials during their decomposition. Metals, for example, can in contrast be remolten and reintroduced to the material cycle with almost no significant decrease in performance.

A comprehensive assessment of the sustainability of glass fibre- and carbon fibre-based composites therefore has to take into account their lifespan, contribution to weight reduction and the amortisation of their embodied energy. In the aviation sector, in particular, weight reductions of 40 - 20 per cent are possible in secondary and primary structures respectively, in comparison to aluminium (Soutis 2005). In specific scenarios the replacement of a steel part by a carbon-fibre component results in an positive environmental impact after 3600km of flight time (Scelsi et al. 2011), illustrating the tremendous contribution composites can make to lightweight construction.

However, within the domain of architecture this issue needs to be scrutinised from a different angle. Buildings are generally immobile, which means that any reduction in weight does not directly result in a more sustainable building, unlike the case of aviation. In order to amortise the embodied energy and the energy consumption of building components, several strategies are currently deployed in the field of sustainable construction. Insulation is added in order to reduce the energy consumption required to heat the building's interior, whereas different forms of sustainable energy creation, such as geothermal heating or the generation of electricity by photovoltaic elements, eliminate the dependency on fossil fuels. Building or insulation materials of natural origin, such as wood, enable a reduction in the CO2 emission balance, as these materials actively bind CO2 during their growth, which can be accounted for in the balance.

In recent years the development and acceptance of sustainable composites has advanced rapidly. Branded as 'green composites', these consist of resins and polymers based on renewable resources, such as plant-derived natural oils as a matrix material and, most commonly, a vegetal fibrous reinforcement. They can be classified into two major fields, bio-degradable green composites and non-degradable green composites (Dicker et al. 2014).

The fibres for the materials can be extracted from the stems and leaves, as well as the seeds, of a variety of plants, thus presenting a bio-derived alternative to synthetic fibres (Dittenber & Gangarao 2012). Unlike synthetic fibres like nylon, glass fibre or aramid, the microstructure of natural fibres comprises different bio-materials, such as cellulose microfibrils embedded in a lignin and hemicellulose matrix, and can therefore be seen as composites themselves (Dicker et al. 2014; Wegst et al. 2015) (Figure 260).

As their microstructure is of natural origin, bio-derived fibres generally display a more heterogeneous behaviour than that of synthetic fibres. At the same time, they are also more moisture absorbent (Dittenber & Gangarao 2012). But besides these drawbacks, in relation to their behaviour they enable the petrochemically independent, local and renewable sourcing of raw materials, due to the large variety and availability of natural fibres. Additionally, plant fibre extraction has a long tradition in the textile industry; consequently the raw material production relies on well-established processes and industrial standards. These circumstances also enable cost-efficient production, which is in most cases lower than that of synthetic fibres. The energy-intensive, complex production of carbon fibre, for example, cannot compete with the relatively simple extraction process of natural fibres; therefore they are usually available at a fraction of the cost (Dittenber & Gangarao 2012).

Meanwhile, constantly improving sustainable thermoplastics and resins based on natural resources such as plant derived proteins, oils and starch offer an alternative matrix material to petroleum-based resins, enabling the production of composite materials which are fully sustainable (Wool & Sun 2005).

For structural applications in the automobile or aviation industry the slightly varying structural properties and the hydrophilic behaviour of natural fibres in green composites are a major factor hindering their application in this specific field. Some secondary structures, however, such as non-structural interior panels, having initially been fabricated in synthetics, are gradually being replaced by sustainable alternatives and are therefore decreasing in environmental impact (Dicker et al. 2014).

In the field of architecture, panelised wood-based composite materials such as MDF (Medium Density Fibreboard), OSB (Oriented Strand Board) or plywood are especially common, due to their cost, efficiency and versatility. The binding material is usually based on petrochemical sources; however, through recent advances in resin technology these substances can be substituted with more sustainable alternatives (Borges et al. 2006).

In contrast to green composites, and with more than a century of development, petrochemical resins are still cheaper and usually deliver better mechanical properties. The relatively new field of sustainable high-tech polymer development, however, is constantly improving. The increasing scarcity of petrochemical resources and global pollution issues related to the excessive use of oil-based materials demands their reconsideration and the promotion of alternatives at a global governmental, as well as corporate, level to improve the environmental impact of manufacturing in general.

Green composites cannot substitute for synthetic materials in every field of application, due to their distinct properties. However, with significantly less energy needed for production (around 20 - 40 per cent of the energy needed for the production of synthetics (Dittenber & Gangarao 2012), and a well-established supply chain, green composites can be seen as a potential candidate for a more sustainable alternative in the emerging field of polymer-bound composites in the built environment.

Illustration of structural hierarchies of bamboo and bone

Bioinspired structural materials (Wegst et al. 2015), p.27

(Image redacted for copyright reasons)

Figure 260 Natural fibre hierarchical substructures

Appendix E: Allopoiesis to autopoiesis - an assemblage approach

Autopoiesis, understood as an abstract system, does not consider material or scale, but operates within a specific domain. Its domain of origin is biology (Maturana & Varela 1980), as outlined previously, but it has been also adapted for example, in the social sciences (Luisi 2007), for architectural theory concepts (Schumacher 2011; Dollens 2015) and computer science (Zeleny 1981).

The distinct domain provides a set of conditions for the autopoietic principle. Autopoiesis within the biological domain operates by means of biology, involving DNA-driven, biochemical processes and interactions (Luisi 2007), whereas autopoiesis within computer science operates on a binary coding platform (Zeleny 1981). This systemic homogeneity exemplifies the distinct domain-dependency of autopoiesis, even though it is not necessarily inscribed in its conceptualisation. In order to extend and unfold autopoiesis within a heterogenous domain the notion of an assemblage in the Deleuzian sense (Deleuze & Guattari 1980) was found to be a helpful conceptual tool.

The logic of an assemblage is defined by a basic structure which is constituted by three theoretical formations – the condition (abstract machine), the elements (concrete machine) and the agents (personae) (Nail 2017) which form heterogenous interdependent entities.

The abstract machine "functions as a kind of local condition of possibility – a set of relations in which elements appear to be meaningfully related"; it enables a "conjunction, combination and continuum of all the concrete elements it conditions" (Nail 2017, p.25). Nail (2017) exemplifies the function of the abstract machine through the reading of a star constellation. He argues that "without the stars in the sky there are no relations between the stars but without relations between the stars there is only radical heterogeneity". In his example the "abstract machine is the relational lines that connect the stars and the concrete assemblage (elements) is the stars that are connected". The personae are, according to Nail (2017), the "the immanent agents or mobile positions, roles of figures of the assemblage" (p. 27).

It is important to acknowledge that the project is not grounded in the idea of a Deleuzian assemblage. It is considered as a tool to dissect and define the individual heterogenous constituents of the system and legitimate their interdependency, and its ontological framework is used to outline the domain of the scenario. It allows intrinsically different actors and entities to be related and identified within a system, such as material, environment or humans, hence generating a heterogeneous domain. This heterogenous domain then provides the distinct stage for a contextualisation within an allopoietic/autopoietic framework.

A solely mechanical scenario, a contrasting example, only works within a self-referential homogeneous domain which might encompass complex inter-domain relationships but does not incorporate a specific dependency or relationship to non-mechanical domains (such as, for example, environmental conditions).

An example of this can be found in the so-called Helix-Tower by Konrad Zuse, which illustrates a highly elaborate mechanical self-generating system which he developed in the context of his research into the technical germ cell (Bock & Eibisch 2017). The apparatus generates a tower-like structure merely through the means of mechanical movement and actuation. It is self-referential in the sense that there is no distinct dependency or external parameter that the structure reacts or adapts to. Even though there is a distinct energetic input in the form of physical movement, it does not possess a generative output which exceeds the means of its own generation.

Hence the Helix-Tower can remain in the mechanical domain without causing friction with other domains. This concept contrasts with the one proposed in this scenario.
Similar to the Helix-Tower (Bock & Eibisch 2017) it employs mechanical means for the generation of a structure. However, the generation of the structure is inherently dependent on environmental parameters, namely the light intensity of the sun. The structure then is then employed for a remediation strategy to transform the surrounding environment, initiating a biological colonisation process which ultimately impacts on the ecology and human settlements of the area.

The scenario can be addressed in two stages. The first part investigates an allopoietic process of structure generation dependent on environmental conditions. The second, speculative scenario investigates the emerging ecology between the demonstrator and the environment, which ultimately results in a remediation process.

As outlined before, the project can be understood as an assemblage where the distinct constituents can be identified based on their contribution and role within the system. Deleuze & Guattari (1980) identify three distinct constituents within an assembly – the condition (abstract machine), the elements (concrete machine) and the agents (personae) (Nail 2017). In accordance to the presented scenario presented, the distinct condition could be understood as the environment while the elements are represented by the demonstrator. the dynamic agent is the material which mediates between the demonstrator and the environment.

These elements also constitute the generative agents presented in the scenario. A distinct environmental input is autonomously translated into a structure, which can be understood as a form of self-generation. The generated structure, however, does not generate itself, hence it could be understood as autonomous allopoiesis – systems that autonomously generate "something different from themselves" (Buchinger 2006, p.362).

The second stage of the scenario, however, is concerned with the distinct ecology between the demonstrator and an emerging fauna. The fauna, in this context, represents a biological autopoietic unit. The scenario envisions a gradual biological colonisation of the structure while the system would provide a supply of water through fog-harvesting. Through the dependency between fauna and structure the demonstrator becomes an integral part of the input to an autopoietic system. Dollens (2015) describes such systems with a distinct interface between architectural tectonic and active biological systems as autopoietic-extended architecture.

Helix tower

The Helix-Tower by Konrad Zuse Automated Con- and Deconstruction (Bock & Eibisch 2010) p. 714

(Image redacted for copyright reasons)

Figure 261 Helix-Tower, Konrad Zuse (1993) left retracted, right extended

Appendix F: Contemporary biotechnology

This paragraph discusses the advancement of biology to the field of synthetic biology. However, the project does not employ any genetic modified organisms (GMOs) or techniques applied in field, this discourse is nevertheless considered relevant for the future potential of active textile microbiomes.

The concept of an active textile microbiome as a material system can in this context be understood as an open framework for bio-active materials. It enables future developments within the field of biotechnology to be deployed within a spatial and fibrous setting, and therefore contribute to new materials with distinct biological features. The emerging field of synthetic biology, in particular, plays a significant role in this context.

The science of synthetic biology enables access to the functional layer of a cell, the DNA, thus enabling not only the culturing and replication of cells but also the "programming" of their function and behaviour (Baldwin 2012). The DNA and its function within a living organism, was discovered in 1953 (Watson & Crick 1953). Following this ground-breaking discovery a new field of science, synthetic biology, arose (De la Bédoyère 2005). Synthetic biology is understood as "an emerging discipline that combines both scientific and engineering approaches to the study and manipulation of biology" (Joyce et al. 2013).

It is based on the understanding that biology operates on a DNA code resembling a complex information (transmission) system based on the interaction between various chemicals and enzymes. All life on earth depends on this elaborate principle of biological information management and transfer.

Methods to manipulate specific features of living organisms through selective breeding, therefore actively contributing to the modification of their DNA, have been widely applied throughout history (Bud 1994). Very few of our plant and animal food sources have not been in some way altered by humans (Kingsbury 2009). Synthetic biology, however, operates on a different level, enabling access to the "building plan of life", the DNA, directly and allowing biological systems to be engineered and altered (Baldwin 2012). This induced a shift within biology, transforming the field from its, to date, mostly observative, analytical character towards a creative, engineering-based potential.

Understanding and being able to (re)write that code has disrupted several industries, from food production to medicine (Nesbeth 2016). At the same the technology has sparked many ethical concerns about its application and its impact on humanity, society and the environment (Bauer & Gaskell 2002). However, the focus of this excursion into the field of synthetic biology is not to explore the complex ethics of biotechnology but to understand the

DNA infografic

https://www.livescience.com/37247-dna.html

(Image redacted for copyright reasons)

Figure 262 DNA and RNA structure and molecular constituents

Functional DNA parts. An example of functional parts in a DNA sequence: promoter, operator, coding sequence (cds), and terminator

Guided Growth - Design and Computation of Biologically Active Materials (Zolotovsky 2017) p. 38 fig. 2.2.2.

(Image redacted for copyright reasons)

Figure 263 DNA Code, A,T,C,G nitrogenous bases and individual functions. Zolotovsky (2017) underlying hierarchical principles and functionality of living systems for an investigation into the active textile microbiome.

The science of Synthetic Biology borrows terms from engineering and computer science to describe the functions and features of living cells. Modularisation and characterisation of different (DNA-based) parts and devices in a modular system enables the assembly of functional circuits which are then executed by the manipulated cell (Ellis et al. 2011). A constant development of new parts and components are categorised and organised in registries. Biobricks™ is one approach which aims for the standardisation of functional biological building blocks (Canton et al. 2008). The idea is to develop a library of parts which can be assembled into a cell-based living system according to the desired functionality. (Zolotovsky 2017).

For a textile microbiome the technology would add another layer of design engagement and functionality. The outcome would not only depend on parameters like fibre quality, geometry and the active organism and its natural behaviour on the fibre, but could also involve the actual designed functionality of a living organism. Where previously the organism and its function within the system was predetermined by its natural behaviour, synthetic biology can unfold another subdomain within the design process of the composite(Figure 264).

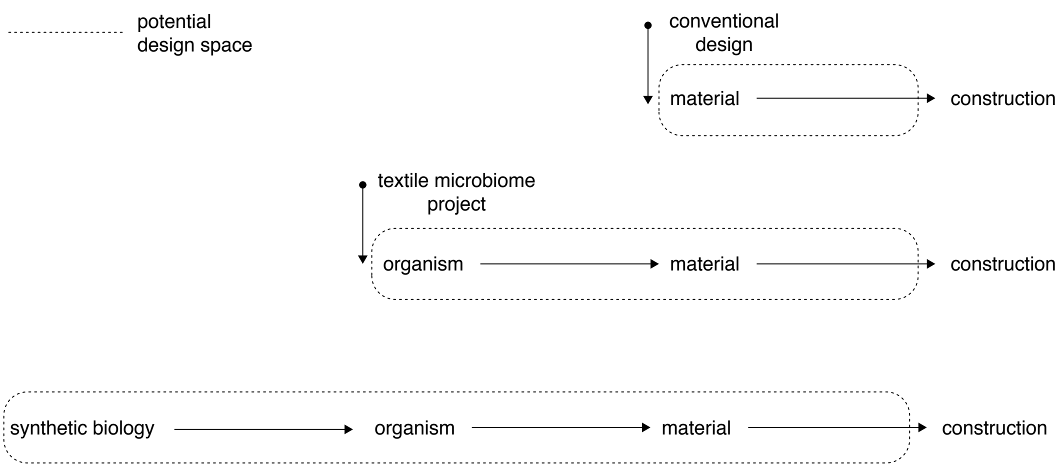


Figure 264 Potential design spaces

Appendix G: Fabrication and application scenario

Ttextile systems offer an expansive repertoire of morphological, geometrical and structural possibilities for potentially numerous spatial configurations of a textile microbiome. Figure 266 illustrates a potential use-case and production scenario developed around the implication of a bacterially active material in established textile processes such as knitting, weaving or winding. The raw material (1) is submersed in a microbiological solution (freeze-drying buffer and active microbial culture), thereby inoculated with a selected microorganism (2). The following step is to freeze-dry the substrate (3) and wind it onto shippable cones. Freeze-drying is commonly used to conserve and store microorganisms in a dormant state, and is widely applied for many species (Morgan et al. 2006). This process allows the storage and transportation of the finished material in a dry environment without having to maintain certain levels of humidity or additional nutrition. This would similarly ensure safety of use in conventional textile machines. Once processed into the desired shape the material can be activated by reviving the organisms, by establishing the specific environment suitable for their metabolic activity. The production and use-case scenario outlined earlier would allow a seamless integration into conventional fabrication systems through the integration of a semi-finished textile material, which is only distinguished from other textile materials by its designed microbiome on a nano scale (Figure 267). In contrast to a conventional textile or composite manufacturing process (Figure 265), two additional steps, inoculation and incubation – derived from biotechnology – enable the embedding of specific bio-(re)active features within textile systems (Figure 268).

The previous paragraph outlined the physical requirements for a microbiome-based material system and unfolded the potential of textiles as a substrate material to be harnessed for a variety of spatial applications. The projects described in the previous chapters employ a range of microorganisms as agents to transform or activate materials. The design process involved selecting specific organisms extracted from a naturally occurring strain, culturing and applying them to a substrate. Hereby, their distinctive behaviour and metabolism remains unchanged.

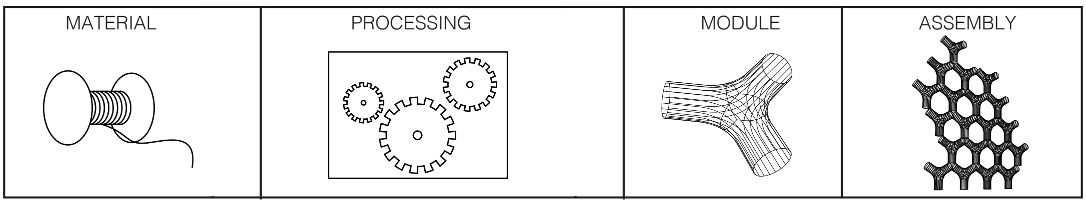


Figure 265 Conventional textile/ composite manufacturing and processing

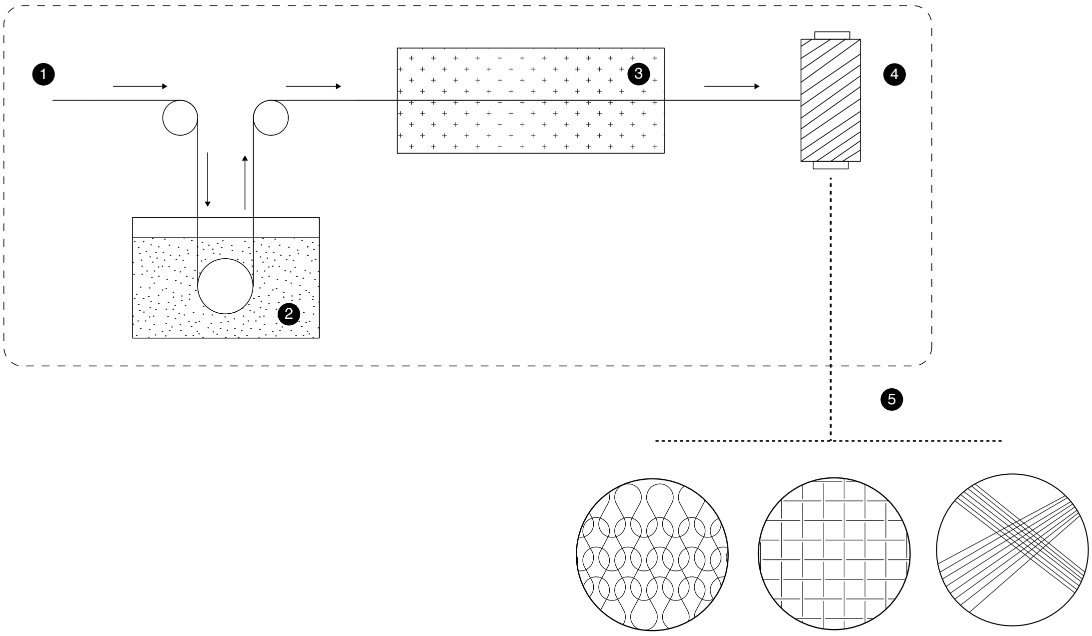


Figure 266 Conceptual material fabrication pipeline

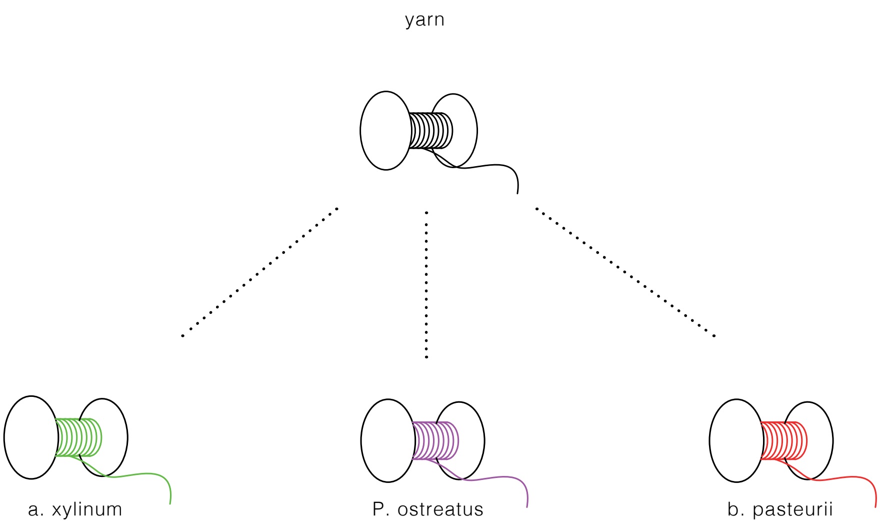


Figure 267 Different textile microbiomes on textile substrate

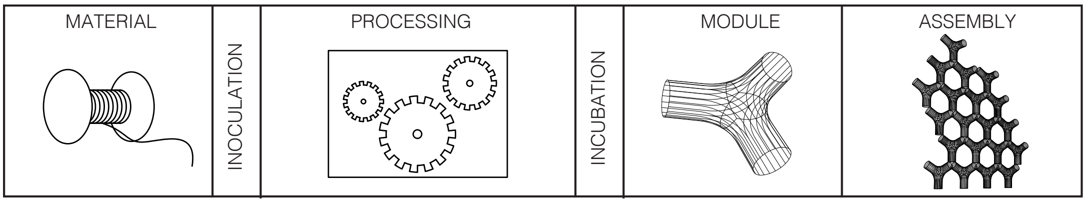


Figure 268 Suggested process, including additional steps of inoculation and incubation

Appendix H: Etude

The term étude (study) originates in the field of classical music and describes pieces

> contrived with a view to aid the student in mastering special mechanical difficulties pertaining to the technical treatment of his instrument…and pieces wherein, over and above an executive purpose… some characteristic musical sentiment, poetical scene or dramatic situation susceptible of musical interpretation or comment is depicted. (Grove 1900, p.496)

An acquaintance with novel skill sets and procedures is connected with the overcoming of challenges during the making. Adapting new skills for a musical instrument demands persistence, repetition and iteration, which ultimately provides the basis for further improvement. An étude describes a musical piece which elaborates on a distinct motif which is usually derived from a more complex composition in order for the student to acquire certain technical and expressive skills to ultimately master the entire related piece.

The term "experiment", in the context of science, connotes a predetermined setup, pre-set conditions and usually a linear process to validate a hypothesis. An experiment, with its distinct protocol, can be understood as the intermediate step between hypothesis and scientific "truth". In this way the researcher has traditionally been expected to remain as objective as possible in order not to interfere with this fragile construct of knowledge generation.

An étude is akin to the concept of an experiment in several ways. Both inherently contain specific protocols and instructions. For a scientific experiment these consist of certain chemicals, materials, distinct parameters, timings and/or ratios. An étude similarly consists of a series of notations which are, in this case, the protocol to be followed. Although they share similarities with regard to their protocols, a dichotomy is apparent in the distinct role of the person executing them.

The researcher functions, as discussed above, solely as an objective executor without generative authorship. The musician also has an executive function but, in contrast to the classic scientific experiment simultaneously embodies hypothesis as well as the result. An étude depends on and is iterated through the musician's distinct interpretation and skill set, making him/her the most significant factor within the process.

The études mainly employ adapted scientific methods; there is the temptation therefore to understand them as "experiments" in terms of their structure, protocol and documentation. This format was initially chosen as a vehicle to improve cross-disciplinary communication. Gradually adapting to the scientific practice and its structure enhanced the discussion of the ideas with specialists in the field. The adaptation of the format was a gradual process which is visible in the varying depths and detail in which Etudes 1-3 were executed. In the context of the personal experience, however, the conception and execution were based, in contrast to what the final documentation might suggest, on a highly iterative, non-linear process.

The personal challenge of becoming familiar with and applying new knowledge, partly through improvisation and interdisciplinary projects, triggered the thinking processes which led to the wider contextualisation of the work, as well as informing the large-scale case-studies. This active participation and transformation made the researcher an integral part of the studies and the thinking processes which are embedded in the work (Frayling 1993). Therefore, it was found to be more appropriate to introduce the term “études” for this chapter.

The études can be understood as investigations into strategies and processes for larger-scale case studies. They identified and applied different methods to establish a textile microbiome and test its functionality within a textile structure. At the same time, the results of the études are used as a foundation and starting point for discussions with potential collaborators.
In this respect the results and processes of Etude 3 initiated a collaboration leading to the successful “column” demonstrator (Beyer, Suarez 2018), which will be discussed in detail throughout Chapter 6.

Appendix I: Collaboration Column project

The project evolved from the results and insights gained from Etude 3. A common interest could be found with fellow ArcInTex Early Stage Researcher Daniel Suarez, who is investigating augmented knitting structures in the context of architecture in his research. This offered an opportunity to explore the behaviour and agency of an active textile microbiome on a scaled-up textile structure. In collaboration with Daniel Suarez, and based on the results of Etude 3, a concept was drafted.

Increasing the scale posed several challenges in relation to the development and manufacture of the material, as well as to the treatment method. Therefore the project benefited from collaboration with an experienced commercial company, as well as a textile research institute.

The concept, which emerged from the collaboration with Suarez, was presented to Soletanche Bachy (France) and Eurecat (Spain). Soletanche Bachy is a commercial company operating globally, with long-term experience in geoengineering. The company developed a system to employ *S. Pasteurii* for underground solidifications. Etude 3 had already been executed with the support of Soletanche Bachy, and the company expressed interest in further collaboration.

Eurecat is a Spanish research institute specialising in knitting and weaving technology, as well as in textile-based composite materials. Their expertise encompasses consulting as well as manufacturing research for textile production methods.

Both companies agreed to support the project, which enabled a cross-European collaboration between two commercial companies and two academic institutions. Besides offering an international knowledge exchange, the collaboration also implemented the paradigm of the ArcInTex programme to foster synergies between commercial practice and academia.

Appendix J: Material selection

As jute fibres are processed into a wide range of raw textile materials, another series of tests was necessary to determine the most suitable jute material. The following specifications of natural jute twines were tested (supplier: ropesource UK)

1. 1/12 Extra fine natural jute twine 1mm
2. 1/96 Thick natural jute twine 3mm
3. 2/16 Thin natural jute twine 1.5mm
4. 3/16 Standard natural jute twine 2mm
5. Polished jute twine 2mm

An assessment of the characteristics of these in terms of their behaviour determined the final material selection. The test incorporated a preliminary knitting test of bundled jute confined in a cotton sleeve. The individual jute threads were bundled to reach a material diameter of around 10-12mm, which was selected in accordance with the anticipated structure as well as the anticipated manufacturing methods. Two samples with the most promising characteristics in relation to handling, flexibility and knit-ability were selected. These were:

1. 10 x 1/12 twine 1mm, 8 x 2/16 twine 1.5 mm (Figure 269 , 1)
2. 10 x 1/12 twine 1mm, 8 x polished jute twine 2mm (Figure 269 , 2)

These samples were knotted to one loop, simulating the smallest module of a knitted structure, in order to examine the influence of the geometry on the treatment. The samples were tested by applying the method described in Etude 3, undergoing two cycles of submersion treatment (in the bacterial and the calcifying solution).

Following the treatment, all the samples showed clear signs of calcite deposition upon visual examination (Figure 269). The deposition on Samples 1 and 2 was increased as expected in comparison to Samples 3-7, which is accounted for by the enhanced surface area generated by the bundled fibre array. The individual fibre Samples 3-7 were successfully calcified, but in a non-homogeneous pattern (Figure 270).

The tests, again, suggest a correlation between the overall surface area of the sample and the calcite deposition. As Samples 3-7 show a very similar deposition pattern, the calcite deposition process is related to the fibre morphology and array rather than to the actual material .

Figure 269 Material test: left, untreated, right, treated sample (two treatments)

Figure 270 Single fibres after two treatments

Appendix K:

The colum project was awarded the Autodesk/ACADIA emergent research Award 2018 at the ACADIA conference in Mexico City 2018. (http://acadia.org/news/6W7TT9)

The installation was exhibitied at the Bow-Arts Trust open studio days (Studio Ian Kiaer). Furthermore, the project was presented at the International Conference on Composite Structures (ICCS21) in Bolognia (presentation: Bastian Beyer) and at the international Textile Conference in Aachen, Germany (presentation: Daniel Suarez).

It also was published in the following online magazines:

-Dezeen (https://www.dezeen.com/2019/01/16/bastian-beyer-knitted-design-material/)

-Springwise (https://www.springwise.com/architects-use-knitted-fibres-to-make-a-building-column/)

-Treehugger (https://www.treehugger.com/sustainable-product-design/knitted-textile-building-material-bacteria-bastian-beyer.html)

-Archi.ru (https://archi.ru/news/82335/kak-iz-vyazanoi-truby-pochvennykh-bakterii-i-specrastvora-sdelat-zhestkuyu-kolonnu)

-Material District (https://materialdistrict.com/article/knitted-biocomposites-structural-systems/)

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