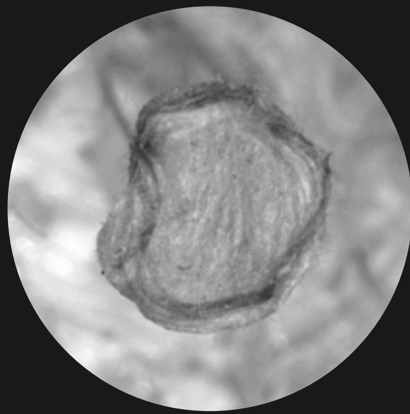
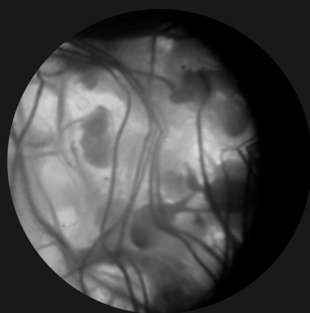
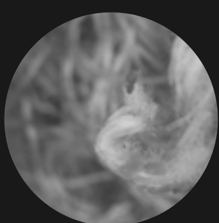
Master Thesis
Jiwei Zhou
August 2019

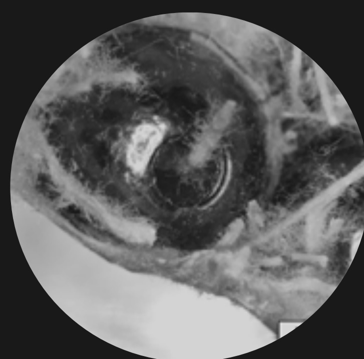


INTERWOVEN: — DESIGNING — BIODIGITAL

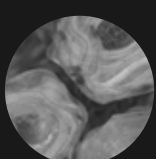


OBJECTS — WITH PLANT ROOTS





EXPLORING — MATERIAL STRUCTURE — AND EXPERIENCE



This ptoject is based on Interwoven, a plant root textile created by Diana Scherer, in collaboration with Material Experience Lab of Industrial Design Engineering faculty of Delft University of Technology, the Netherlands. This project in under non-disclosure agreement with Diana Scherer, so some research results have been only included in the confidential appendix.

Project
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Designing BioDigital Objects with Interwoven
Exploring Root Structure and Experience

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-

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In Collaboration with
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PREFACE

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"The world will be moving from things that are fabricated to things that are farmed; from things that are constructed to things that are grown."

- Carol Collet, 2018

About 140 years ago, Arts and Crafts Movement began in Britain and flourished in Europe and North America between 1880 and 1920, influencing Japan in the 1920s. Against industrialization, avant-guards called for traditional crafts and a sense of nature back in daily life. Paris metro station Abbesses, by Hector Guimard (1900); Lithograph by Alphonse Mucha (1897); Lamp by Louis Comfort Tiffany (1900–1910); Wall cabinet by Louis Majorelle; Interior of Hôtel Tassel by Victor Horta (1892-3).

Since then, designers, artists and craftsmen never stop discussions of anti-industrial. However it is interesting to see that, every time and age has its own way of making it happen. From aesthetics, to the materials designers use, to the way of manufacturing in our age.

On the ride of collaborating with living organisms to produce everyday objects, we see that today, many designers, artists, material scientists, and biologists are working together for digital biofabrication.

Diana Scherer is one of the pioneerings in our age. She has been training roots, using digital fabrication, to form beautiful textiles called Interwoven since 2015. In this project, I am very lucky to learn from her and collaborate with her and Material Experience Lab established by my supervisor Elvin Karana in TU Delft.

I am a second year master student in Design for Interaction. My interest in biology and materials has driven me to go deeper into bio-digital manufacturing and bio-material design during two years of studies. In this project, I am trying to explore development of Interwoven in the perspective of material structures to create everyday objects.

Here, I want to thank my supervisors Elvin and Jun for their professional help and advice. And I want to thank Diana Scherer for sharing her many years' experience with Interwoven.

Thank everyone who helped me in the process for studies of material samples. Thank Mascha and Tessa for technical support in the Applied Lab.

Thank you all, my dear friends, for being there during my hard times.

EXECUTIVE SUMMARY

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This thesis is the graduation project of the master study: Design for Interaction at Delft University of Technology. In collaboration with an visual artist Diana Scherer in Amsterdam and Material Experience Lab in Industrial Design Engineering faculty, the project follows material driven design for a material called Interwoven developed by the visual artist. The material has shortcomings and is too fragile to be applicable product material, but it has great potential to be a sustainable substitute material for design. The goal of this project is to follow Material Driven Design method developed by Elvin Karana in the same faculty, and develop Interwoven into a durable and applicable material for product design.

Researching the potential of mycelium design, the main question for this thesis is defined as follows:

How to make Interwoven more durable and applicable in people's daily life through re-designing material structure?

There's a pre-research of the graduation project, done by the author and other two master students from the same track in the faculty. As a result from the pre-research, a material tinkering taxonomy has been summarised to help designers start their experiments for material development. This project takes "altering material structure" as the challenge and perspective.

Besides that, the project also emphasizes the digital layer of manipulating a bio-material. With the help of one of the project supervisors - Jun Wu's research in the generative design field, and the preminary knowledge in parametric design and programmable material of the student, the project managed to use digital manufacturing tools for material structural change.

During the material understanding phase in the method, more than 50 experiments and iterations have been conducted to investigate material structure possibilities. Amongst the number of samples, insights have been concluded and a mapping of root behaviour has been made. Experiential studies with potential samples have been conducted.

From material understanding phase, it has been found that Interwoven not only can weave horizontally, but also vertically with 3D printed porous units and serve as glue, to form a stronger thus more durable holistic volume. Extruding patterns on surface, serving as the skin of the structure, invite people to inspect and touch.

A conflict and collaboration between natural growth of roots and human manipulation is presented through the root structure. Therefore, a material experience vision is created:

to exhibit the glue-ability of Interwoven through a daily object co-created by roots and digital manufactured structures and bring forward the collision and collaboration between natural growth and man-made world.

With the Vision as basis for the idea generation, and technical performance tests for the co-creation samples, five product concepts have been developed. Considering to apply the product in daily scenarios and fitting it to the vision, the final concept is to use roots growing through porous descrete beads to form 3D volume and imitates mass-produced IKEA ALSEDA puff. The imitation would invite people to inspect and try out the strength of the compositional structure, which will surprise people with a conflict between delicate pattern and the strength of product body. Technical tests have been done to investigate into the compressive strength and porous units have been improved.

The thesis concludes with a self-evaluation of the design goal: both technically (durability) and experientially (applicable, blend of nature and man-made). Technically, durability is tackled with creating compositional structure with 3D printed porous units, and experientially creating a hybrid blend by this structure and a skin of growing traces. And a set of recommendations for further research and development to make the material more various, sustainable and ethical. The main elements recommended include exploring more porous structures, scaling up the product, preventing molds, other material potentials, making production more sustainable and end life recycling.

TERMINOLOGIES

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Interwoven
Textile material grown from plant roots developed by Diana Scherer. The start point of this thesis project and will be explored and developed during the project.

Material Driven Design (MDD)
A design method to facilitate designing for material experiences when a particular material is the point of departure in the design process.

Material Tinkering
Sensory encounters and hands-on manipulation in material understanding, whilst promoting design activity oriented to enrich desired experiences in final designs (Notion brought forward by the Bauhaus) - tinkering with the material is to get insights on what the material affords, its technical/ mechanical properties, as well as how it can be shaped/ embodied in products.

Digital Bio-fabrication
It is at the cross field of biology and design, where designers couple biological tools with advanced computer technologies.

Obstacles
The objects put in the way of root growth. They prevent roots going directly downward, but make roots take a detour.

Porous Units
The porous descrete obstacles put in the growing media for roots to glue together. The relationship between roots and poroous obstacles during material tinkering process.

Growing Vessel
A container or space designed for containing seeds and therefore their roots.

Gravitropism
Gravitropism (also known as geotropism) is a coordinated process of differential growth by a plant or fungus in response to gravity pulling on it. Gravity can be either "artificial gravity" or natural gravity. It is a general feature of all higher and many lower plants as well as other organisms.

Material Property vs. Quality
The properties of materials are objective and measurable. They are out there. The qualities on the other hand are subjective: they are in here: in our heads. They are ideas of ours. They are part of that private view of the world which artists each have within them. We each have our own view of what stoniness is. (Tim Ingold, 2011)

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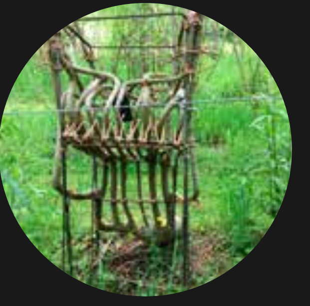

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Project Description

This first chapter of the thesis provides an introduction to the project. It gives a brief explanation of the subject and elaborates with the problem statement and its related research questions. Additionally it presents an overview of the methodologies used throughout the project.

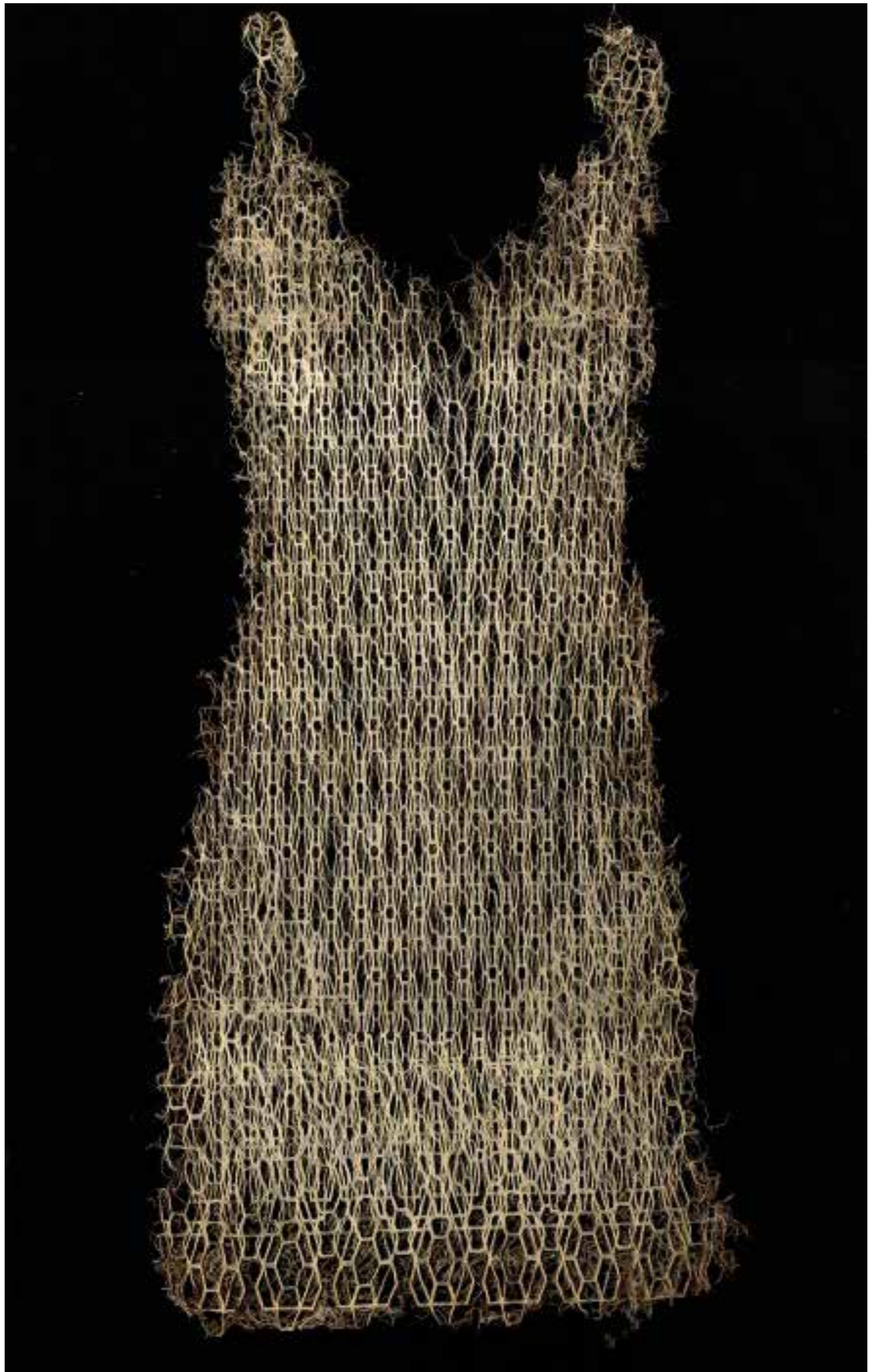

Figure [1]. Interwoven dress as an art piece by Diana

INTRODUCTION

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Artwork 'Interwoven'

Artwork in Collaboration with Roots

Interwoven, simply speaking, is a textile material grown directly by plant roots. Due to human manipulation, the roots grow into patterns designed by humans. It was invented in 2015 by Diana Scherer, a visual artist based in Amsterdam, the Netherlands, and has been developed since then. Due to fragility, it still remains an artistic work. However, Interwoven has a great potential for sustainable product design if further development. Collaborating with Materials Experience Lab of Industrial Design Engineering in Delft University of Technology, Diana Scherer wants to bring an artistic material closer to people's daily life.

Since 2015 she has been using the hidden processes of plant roots for the formation of her work, by making the invisible, visible. Her work comes from a collaboration with nature. Developing a technique to guide the growth of the plant roots, using templates as moulds, the root system conforms to the patterns designed by Diana. She sees the roots as if they were yarn to be woven and braided. Her intuitive approach to the materials creation, which she calls 'Interwoven' started as an art project. Her background as a visual artist and her artistry makes it possible for her to "approach the world of science in an open minded way and to make it accessible to the spectator."

Potential of being a Sustainable Material

Her research has resulted in an unprecedented material. A textile of plant roots is a new material. So far, plant roots have not yet been used for the production of a material. In contrast to comparable textiles made from natural fibers, the material itself weaves. It produces itself through the dynamic search of the plant for nutrients and water. Which Diana mentions is, "exciting because I never know exactly how the roots develop. They follow my templates but also find their own way, its an enjoyable process". The material is created from a subterranean living biomass, which continues to produce itself as long as there is enough power, light and heat. CO_2 storage in living biomass is seen as one of the ways to reduce the CO_2 concentration. Plants absorb CO_2 and fix the carbon in organic compounds. This process is known as Carbon Fixation (wikipedia, 2018), a unique quality of the process.

Figure [2]. Interwoven with grasses

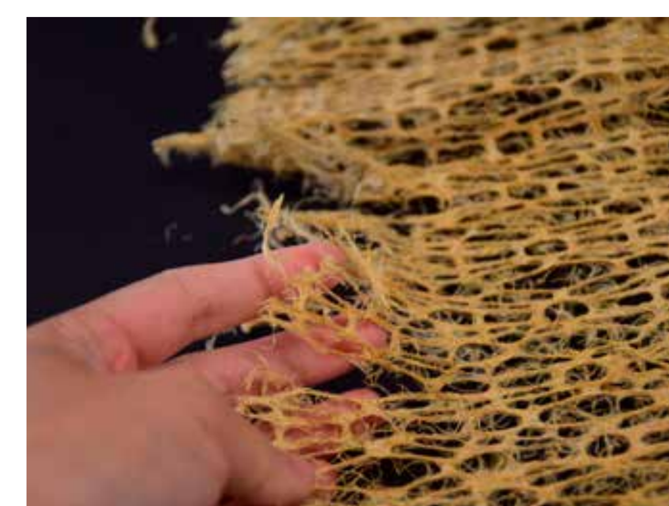

Figure [3]. Interwoven textile sample

The above paragraphs are adapted from a pre-research for a broad understanding of Interwoven and its potentials. The research is done by three master students from the same faculty including the author of this thesis.

Growing Design x Digital Biofabrication

Interwoven represents collaboration between human purpose and natural organism. This approach is called Growing design, which is distinctive within the notion of Myers', BioDesign, that is "the emerging and often radical approach to design that draws on biological tenants and even incorporates the use of living materials in to structures, objects and tools (Meyers, 2012, p8). Growing Design moves beyond the drop-in replacement of existing materials technologies (Camere & Karana, 2017) and challenges current industrial consumption and production because it offers the opportunity to co-create with nature and shift the paradigm of production towards more sustainable solutions (Karana, 2018). It incorporates a focus on developing novel materials through controlling the growth of organisms, where an organism is shaped by the designer into a desired form. Several artists are exploring the creation of novel materials by utilising the natural processes of the growth of living organisms, such as bacteria, algae or fungi (Karana, 2017). Their process is characterised through a hands-on exploration and a bottom up approach (Karana et al., 2015) driven by the creation of the material, which allows opportunities for achieving new and unconventional materials experiences (Rognoli, 2015). Often designers who work with biology envision a far, provocative future (Camere, 2017) which is grounded in Speculative Design (Dunne & Raby, 2013); however Growing Design is rooted in the analysis of the present manufacturing paradigm, working towards new ways to sustain our existence (Camere, 2017), as the materials tend to be harmless to the environment and biodegradable.

Interwoven does use digital fabrication to produce precise patterns. Therefore it has been classified into the cross area of growing design and digital biofabrication, because the template is digitally designed. Figure [4] shows the taxonomy created by Camera and Karana. Falling into the same area are the Mycelium Chair by Eric Klarenbeek and Silk Pavilion by MIT Media Lab. The positioning of Interwoven uses a model which maps four approaches using biology for design purposes, created by S. Camere and E. Karana in 2017 (Camere and Karana, 2017). They have grouped the works that cross-fertilize biology and design into four categories: (1) augmented biology; (2) biodesign fiction; (3) digital biofabrication; (4) growing design.

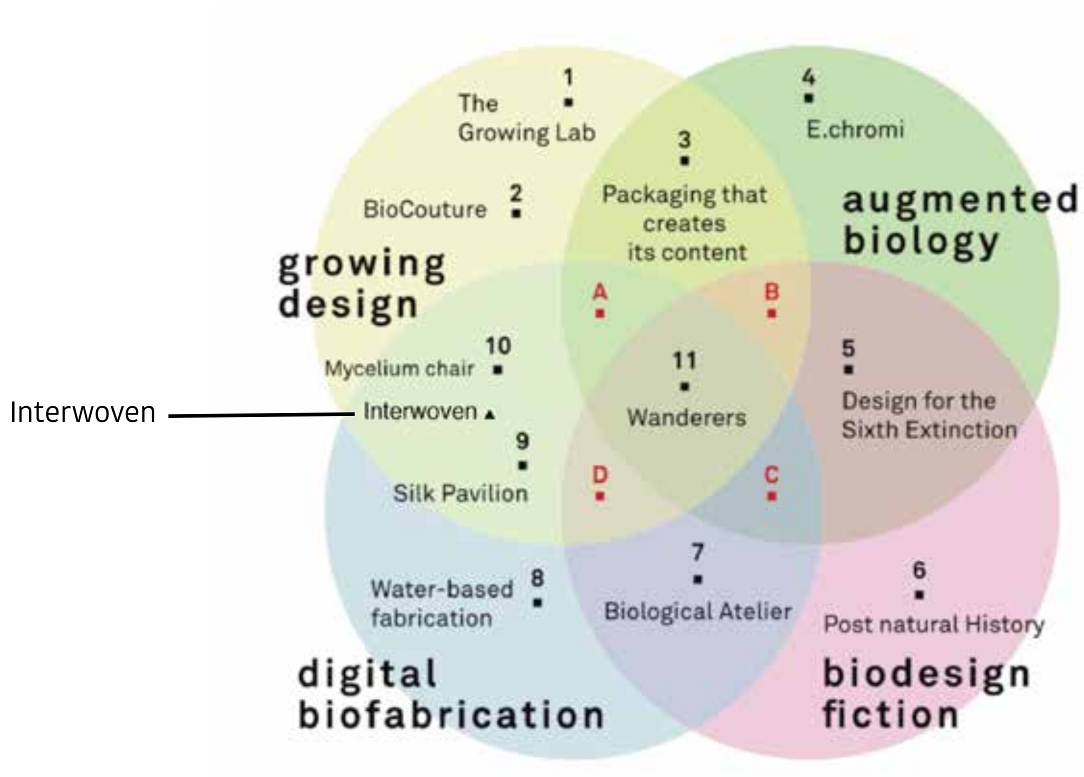

Figure [4]. Four approaches cross-fertilizing design with biology and related cases adapted from Camera & Karana 2018

The above paragraphs are adapted from a pre-research for a broad understanding of Interwoven and its potentials. The research is done by three master students from the same faculty including the author of this thesis.

PROJECT SCOPE

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Diana has an interest in developing Interwoven into a commercial product. Her goal in the long term is to develop the "bio-fabricated material into a sustainable and applicable material" and bring it closer to people's daily life.

Since the material is constituted of plant roots it is biologically manufactured and degradable. Therefore the challenge lies in creating a more durable and applicable material.

She is collaborating with product design masters students from The TU Delft to investigate how to "strengthen the material and perfect the design of the subterranean templates". A broad desktop research has been done by three master students including the author to map out the development possibilities of Interwoven.

This research paves the way for further tinkering with Interwoven in four suggested directions, including: (1). material ingredients (2). growing conditions (3). material structure (4) material processing. Figure [5] presents a taxonomy of these directions and summarizes what specific variables could be played with in order to develop the material.

Figure [5]. Tinkering taxonomy for Interwoven summarized from pre-research

The project will use Material Driven Design method to research and design with Interwoven in the direction of developing material structure. Digital fabrication techniques will be used, due to their great potential in bio-design field.

Material Driven Design Method
The project will explore the possibilities of Interwoven to make materials through Material Driven Design (MDD) method (Karana, 2015). The methodology will be introduced in next sections.

Digital Fabrication
Advanced digital manufacturing will be used for designing material structure. It is Diana Scherer's vision to incorporate additive manufacturing such as 3D printing into the material. Other means of digital fabrication will also be explored, such as generative design and programmable materials.

Project Direction: Plant Root Structure
Interwoven is seen as a semi-developed material within the framework of Material Driven Design (MDD) (Karana, Barati, Rognoli & Zeeuw van der Laan, 2015) due to lack of durability (definition from Cambridge dictionary: continuing to be used without getting damaged) according to Diana Scherer. This graduation project takes the direction of changing material structure to increase material strength as a strategy for improving durability in the first step of MDD. The following steps are: Experiential & Technical Characterization, Benchmarking, Formulating Material Experience Vision, Experience Vision Pattern Study and Material Conceptualization. The final aim of the project is to demonstrate a material structure concept to show the potential of the designed material structure for a daily product.

METHODOLOGIES

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Material Driven Design (MDD)

The MDD method is a new methodology for materials exploration and design when a material is the departure point of the design process because the material is new or under developed, in this case Interwoven. Grounded on the notion of Materials Experience (Karana, 2009) and combining practical experimentation, user studies and envisioning. It is a journey that involves an explorative process of creation and evaluation, through tinkering directly with the material, that leads to insights about the material properties and experiential qualities, to a vision that describes the quality of the material interaction in a particular context and ends with a meaningful material product application.

The steps of the method are: (1) Understanding The Material: material tinkering, technical and experiential Characterization, benchmarking. This step includes tinkering with the material to get insights on what the material affords, its technical/mechanical properties, as well as how it can be shaped/ embodied in products; material benchmarking to position the material amongst similar and/or alternative materials, to generate insights on potential application areas, emerging materials experiences and other emerging issues within the design domain; and user studies to explore how the material is received by people, how it is appraised (i.e., experiences related to aesthetics, meanings, and emotions), as well as what the material makes people do (Giaccardi & Karana, 2015). (2) Creating Materials Experience Vision. The Materials Experience Vision expresses how a designer envisions a material's role in creating/contributing to functional superiority (performance) and a unique user experience when embodied in a product, as well as its purpose in relation to other products, people, and a broader context (i.e., society and planet) (Karana et al., 2015) (3) Manifesting Materials Experience Patterns, to understand how/when other people experience or interact with materials in a way he/she envisions, rather than using intuitions and guesstimates on possible experiences and interactions. (Karana et al.) (4) Designing Material / Product Concepts.

As depicted in figure [6], the MDD process starts with understanding the material and ends with a product and/or further developed material concept or a product concept.

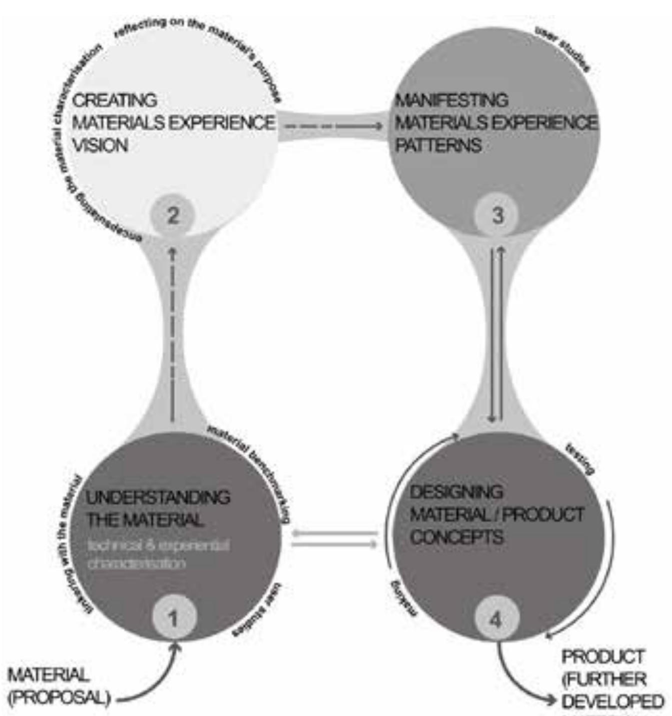
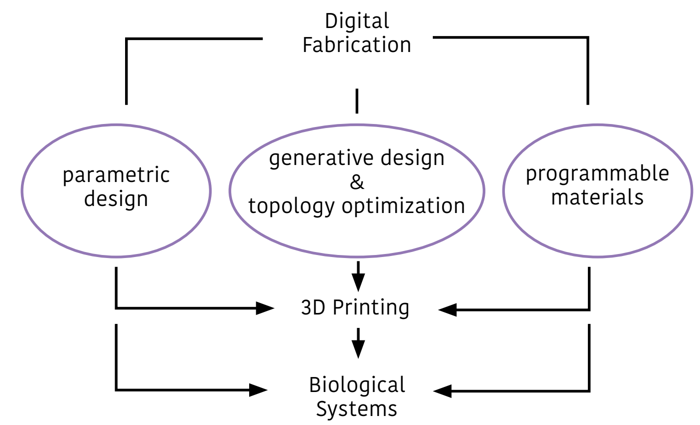


Figure [6]. Material Driven Design (MDD) method.
Adapted from Karana 2015

Digital Biofabrication

Digital Biofabrication means when designers couple biological tools with advanced computer technologies, in a digital biofabrication approach (Camere and Karana, 2017). In this approach, designers use advanced computational tools to 'hack' the biological systems. Their design process is thus highly influenced by such tools. (Camere and karana, 2018) Tools such as parametric design, generative design and programmable materials will be introduced in this section.



Parametric Design
Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response (wikipedia). Parametric design can help designers to map desired material properties through modeling different areas on a material with a certain algorithm. For instance, lower density in areas of eyes and nose on a mask. Forms and structures of the design are precisely defined by parameters and designers can change them by adjusting. Such as, changing size, generating random parameters and forms according to needs. A benchmarking of current practices of parametric design has been done and the main functions of parametric design are concluded.

Figure [7]. 3D Printed Midsoles for Runner Shoes, New Balance, 2015.

Gradience of Material Properties:
Material properties can have different properties in different parts. This is realised through defining parameters of desired properties specifically in parts, by using parametric design software like Grasshopper in Rhino. For instance, figure [] shows New Balance running shoe designed by Nervous System studio in 2015. The studio carried out a set of experiments, using a grid of underfoot sensors that recorded the force as the foot strikes the ground and pushes off. Foam structures are used, since they have a low relative density and are highly porous, giving them the unique property of being both lightweight and strong. "We wanted to use the running data to design foams that geometrically adapt to different forces," the studio indicated. The prototype shoes feature flexible porous soles with smaller, more closely gathered holes in areas of the shoe where the foot requires more support – such as the heel and ball. (https://www.dezeen.com/2015/12/06/new-balance-nervous-system-3d-printed-personalised-soles-trainers-footwear/)

Different Functions but the Same Material:
Parametric design can be used to realise different functions of material in different areas in one piece, if the material will be produced using additive manufacturing like 3D printing. In the following example (Biomimicry Chair designed by Lilian van Daal in 2014), the material in one product is divided into different functions: supporting and providing flexibility. The chair is 3D printed as a whole part, but has both supporting and flexibility functions.

Figure [8]. Biomimicry Chair, Lilian van Daal, 2014.

Generative Design

As parametric design, generative design also involves the user gradually tweaking spatial parameters until a desired form is reached. It is responsible for some of the futuristic-looking buildings by Zaha Hadid Architects, MAD Architects and more. However, with generative design, the purpose is fixed, and the parameters are fixed, and the algorithm is decided by computer, mimicking the way organisms evolve in the natural world, producing the most lightweight structures possible. The computer quickly builds all the possible solutions for the user to choose from – learning their preferences as it does so.

As impact, generative design removes the guesswork from the geometry-creation part of the process. With generative design, you essentially tell the computer: “I don’t know the solution, but I do know how to frame the problem.” You start this process by capturing constraints (such as loads or mounting points) and establishing preferences (such as weight, safety factors, and manufacturing techniques). (https://www.dezeen.com/2017/02/06/generative-design-software-will-give-designers-superpowers-autodesk-university/)

Many designers are experimenting with generative design to produce new forms and improve existing products. For instance, Airbus’s bionic partition needed to meet strict parameters for weight, stress, and displacement in the event of a crash with the force of 16g. To find the best way to meet these design requirements and optimize the structural skeleton, the team programmed the generative design software with algorithms based on two growth patterns found in nature: slime mold and mammal bones. The resulting design is a latticed structure that looks random, but is optimized to be strong and light, and to use the least amount of material to build. (https://www.autodesk.com/customer-stories/airbus)

Figure [9]. AirBus’s Bionic Partition, using generative design approach to reach the least weight and most strength. Adapted from https://www.autodesk.com/customer-stories/airbus

Topology Optimization

There is also a technique called topology optimization, which sometimes confuse people with generative design. It is for generating 3D objects, which allows to efficiently evolve the topology of high-resolution solids towards printable and light-weight-high-resistance structures (Wu et al., 2015). Figure [10] shows two models created based on topology optimization and generative design rules (left: topology, right: generative design) The difference is as follows: generative design starts from defining force and constraints, without the limitation of design space; while topology optimization requires users to define a design space as a limitation factor. Topology optimization is done based on load paths, by looking at where the load wants to go between the load points and the fixed body. The result is a reference mesh for later modification. Generative design looks at stress distribution and removed the low stress areas. Designers can use the result as it is. (https://f360ap.autodesk.com/courses/introduction-to-generative-design/lessons/lesson-4-shape-optimization-vs-generative-design) In generative design, there will be many solutions of forms to let users to choose from, but in topology optimization, only one optimal solution will be calculated and presented. Users have options in choosing what much percentage of mass they want to keep.

Since roots have their principles of growing, they do not necessarily follow the generated structure. In this project, TopOpt will be used to optimize the final design, reducing material weight. The TopOpt group provides software for topology optimization (http://www.topopt.mek.dtu.dk/about). It is world leading within development and applications of density based topology optimization methods.

Figure [10]. Left model: topology optimization from a block. Right: generative design model from the constraint and load areas.

Programmable Materials

Programmable Materials consist of material compositions that are designed to become highly dynamic in form and function, yet they are as cost-effective as traditional materials, easily fabricated and capable of flat-pack shipping and self-assembly. These new materials include: self-transforming carbon fiber, printed wood grain, custom textile composites and other rubbers/plastics, which offer unprecedented capabilities including programmable actuation, sensing and self-transformation, from a simple material.

MIT Self Assembly Lab is leading programmable material research and engineering. Their goal is to make true material robotics without robots. Nearly every industry has long desired smarter materials and robotic-like transformation. However, it often requires expensive, error-prone and complex electromechanical devices (motors, sensors, electronics), bulky components, power consumption (batteries or electricity) and difficult assembly processes. These constraints have made it difficult to efficiently produce dynamic systems, higher-performing machines and more adaptive products, until now.

Figure [11]. MIT Self-assembly Lab, Wood Printing.

Figure [12]. MIT Self-assembly Lab, Programmable Carbon Fibre.

A number of recent technologies have been brought together to enable a breakthrough in material performance. These technologies include: multi-material 3D/4D printing, advances in materials science and new capabilities in simulation/optimization software. These capabilities have now made it possible to fully program a wide range of materials to change shape, appearance or other property, on demand.

Take wood, which reacts well to water (Figure [11]). “Cellulose expands when it gets wet, so wetting wood veneer makes it curl,” says Tibbits. “For example, wetting thicker pieces of wood makes them swell with enough force that they used to be inserted into cracks in rocks and moistened to help miners break stone.”

Then, there’s the structure of the material — with wood, this means the direction of the grain — which helps dictate how it transforms. “We’ve figured out how to print custom wood grain by taking sawdust and plastic, combining it into a filament and extruding or forcing it out,” says Tibbits. “This gives us the freedom to design the direction of the grain, which we can then activate by moisture to produce useful, repeatable transformations, like folding, twisting, curling and so on.” (https://ideas.ted.com/a-peek-into-the-brave-new-world-of-programmable-materials/)

However, to program a material uses needs extra chemicals that responds to heat and 3D printing unrecyclable materials as figure [12] shows. “We printed, bonded or sprayed temperature-sensitive polymers onto and within carbon-fiber sheets in very specific patterns, programming it to fold or twist in precise ways,” says Tibbits from Self Assembly Lab.

If growing materials has certain qualities that can be programmed and utilised in a controllable manner, material use can be much more justified.

Figure [13]. WANDERERS: AN ASTROBIOLOGICAL EXPLORATION, 2014. Adapted from: https://3dprintedart.stratasys.com/nerioxmanwandersmushtari

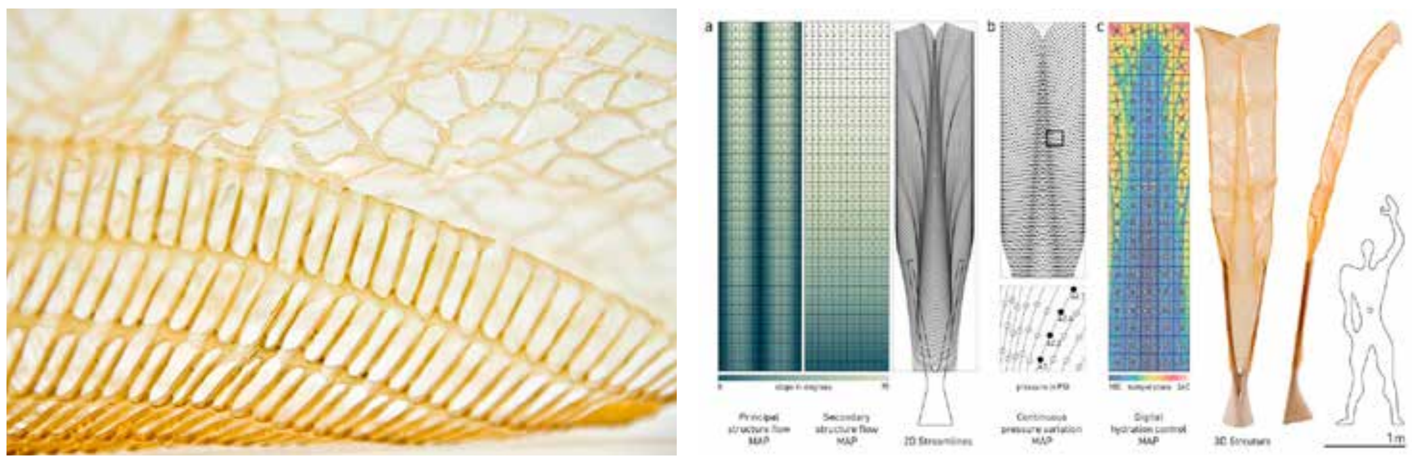


Figure [14]. Water-based 3D Printing, 2018. Adapted from: https://www.designboom.com/technology/neri-oxman-mit-mediated-matter-water-based-digital-fabrication-05-14-2018/

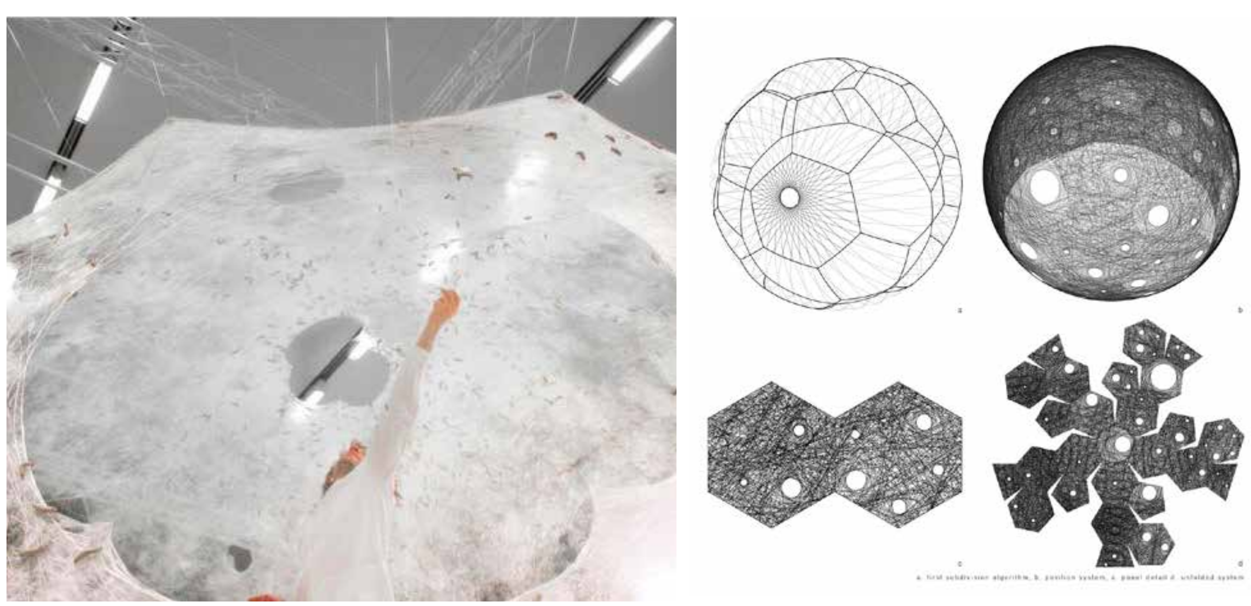


Figure [15]. Silk Pavilion, MIT Media Lab, 2013 Adapted from : https://www.dezeen.com/2013/06/03/silkworms-and-robot-work-together-to-weave-silk-pavilion/

Precedent Projects

Summarised by Camere and Karana (2018), the current practices in digital biofabrication are: Mycelium Chair, Silk Pavilion, Water-based Fabrication, Wanderers and Biological Atelier. Three of the cases are researched in the following paragraphs. The figures are on the left page.

Wanderers

An Astrobiological Exploration, consists of four 3D printed wearables, each of which is designed to contain and generate life-sustaining elements. Exploring the idea of voyaging beyond planet Earth to inhabitable landscapes in the solar system, Oxman's collection is the first color, multi-material, 3D printed range of wearables aiming to embed living matter within 3D structures that augment the environment, enabling visitation to these deadly environments. (https://3dprintedart.stratasys.com/nerioxmanwandersmushtari)

Water-based 3D Printing

Researchers from the Mediated Matter Lab developed a water-based fabrication method to 3D-print biomaterials, harnessing the growth of microorganisms to complete the form of the printed structure (Bader et al., 2016). This biologically derived digital fabrication process forms constructs that utilize graded material properties for hydration-guided self-assembly using a robotically controlled multi-chamber extrusion system which deposits biodegradable composites across length scales. The structures are made of a single material system derived from chitin – the most abundant renewable polymer in the ocean, and the second most abundant polymer on the planet. ground arthropod shells are transformed into chitosan, a chitin derivative, to form a variable property aqueous solution. once printed, constructs are form-found through evaporation patterns given by the geometrical arrangement of structural members, and by the hierarchical distribution of material properties. controlled wrinkling follows. each component will find its shape upon contact with air, and biodegrade upon contact with water. Living matter in the form of cyanobacteria is coated and impregnated onto chitosan samples to enable surface functionalization and impart additional properties such as water resistance and conductivity.' (https://www.designboom.com/technology/neri-oxman-mit-mediated-matter-water-based-digital-fabrication-05-14-2018/)

Silk Pavilion

The project is intended to explore how digital and biological fabrication techniques can be combined to produce architectural structures.

The team programmed the robotic arm to imitate the way a silkworm deposits silk to build its cocoon. The arm then deposited a kilometre-long silk fibre across flat polygonal metal frames to create 26 panels. These panels were arranged to form a dome, which was suspended from the ceiling. Silkworms are then placed onto the dome and produce silk on the existing strucutre. (https://www.dezeen.com/2013/06/03/silkworms-and-robot-work-together-to-weave-silk-pavilion/)

Collaboration between Digital Modelling and Biology

All of the three projects present hybrid objects made by the collaboration between digital modelling techniques such as 3D Printing, and biological matter (micro organism like bacteria, bio-based material like chitin, and living silk worms).

Relevance to this Project

It remains a challenge to transfer the digital-bio objects into something people in their daily life can get access to and use. Most of the current practices in this field remains at a demonstrator/ speculative phase, which presents a futuristic concept, yet not fully functional. Relevant to this project, the production process of the digital-bio object should be considered to be more feasible out of lab environment and the product should be more reliable in its usability.

RESEARCH QUESTIONS

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As guidance for the development of Interwoven, the main research question is as follows:

How to make Interwoven more durable and applicable in people's daily life through re-designing material structure?

The main research question is divided into smaller parts:

Digital Biofabrication
- What are the existing examples of bio-digital fabrication?
- In these examples, how does digital fabrication contribute to bio-design?
- What are the techniques they use?
- How can these techniques be applied to Interwoven?

Understanding Root Structure
- What is the current composition and structure of Interwoven?
- What is the technical properties?
- How can the properties be modified?
- How do these properties change when the ingredients vary?
- What are the most convenient manufacturing processes?
- What are the technical constraints and opportunities?
- What are the experiential properties of the material?
- What are unique sensorial qualities and which are the most and least pleasing?
- Is the material associated with any other material?
- Does the material evoke any meanings?
- Does the material elicit any emotions?
- How do people interact/behave with the material?
- What the properties of developed material structures?
- What are the experiential properties of the developed material structures?

Material Structure and Experience
- What is material structure?
- What are designers' purpose to create new material structures?
- How do people experience material structure?
- Is there an example of recent structural innovation in growing design?
- What is the root structure?
- How to change root structure?

Altering Root Structure
- How to change root structures?
- What difference does the structure make to the technical qualities of roots?

Material Characterisation
- What are the material's unique technical/experiential qualities to be emphasized in the final application?
- In which context would the material make a positive difference?
- What would the material's unique contribution be?
- How would it be sensed and interpreted (sensorial and interpretive levels)?
- What would it elicit from people (affective level)?
- What would it make people do (performative level)?
- What would be the material's role in a broader context (i.e. society, planet)?

Material Concept
- Which material samples are essential for the design vision?
- What are their characteristics?
- Which characteristics are necessary to evoke a certain meaning , emotion or behaviour?
- Which technical characteristics are necessary to evoke a certain meaning, emotion or behaviour?

Experience Vision
- What unique qualities of material contribute to the vision?
- What are other similar design/materials?
- What are their gaps?

Product Concept
- What are the experience vision patterns?
- What will be a meaningful product?
- What is the prototyping method and standard?

THESIS STRUCTURE

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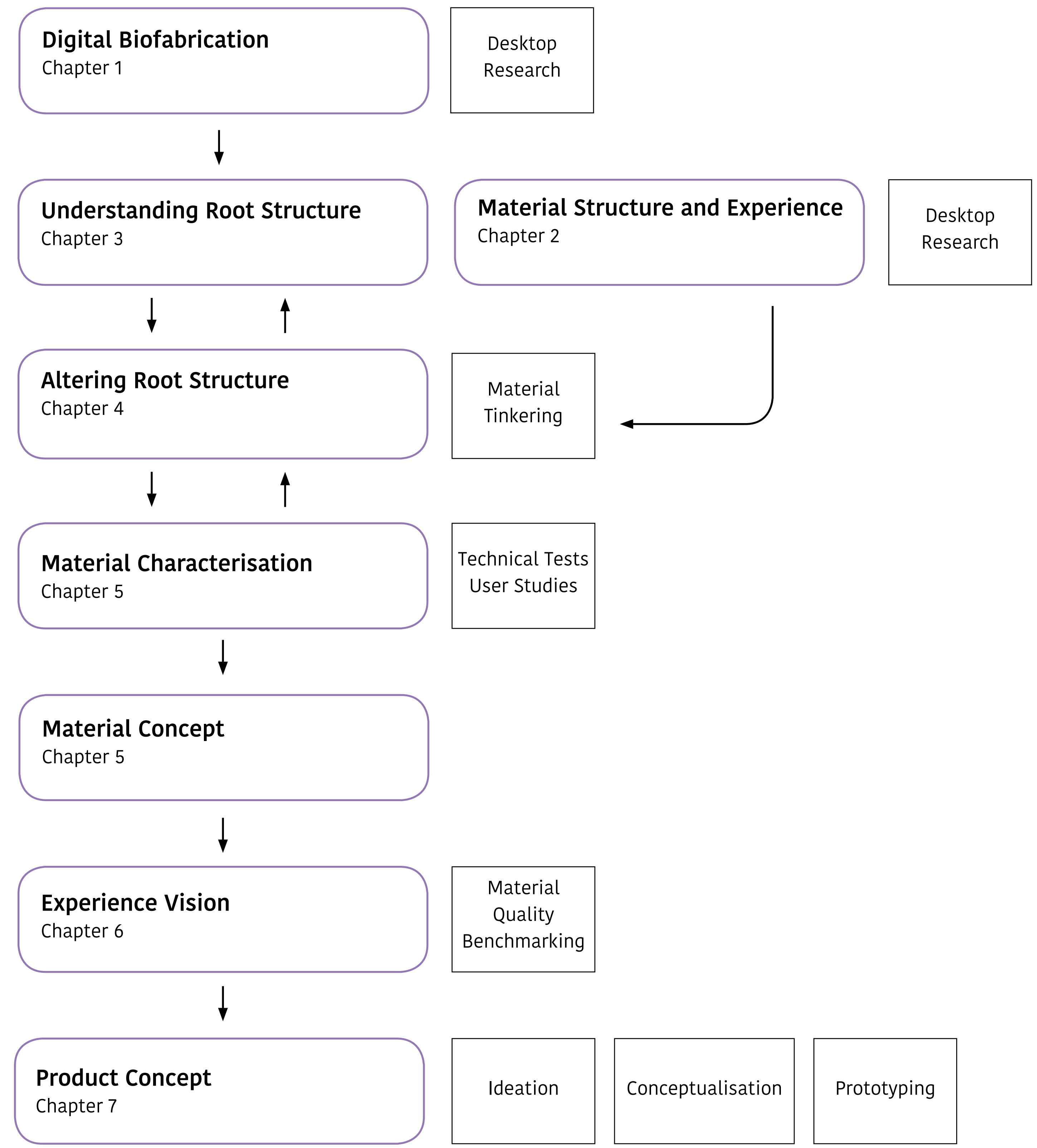

2

Material Structure and Experience

This chapter is about research into material structure, and its influence on material experience. A benchmarking on some famous structural innovation in design is presented and the designs are clustered in different levels of material experience, according to Material Driven Design. This research prepares for the later experiential characterisation of root material structures.

MATERIAL STRUCTURE

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Definition

Structure is an arrangement and organisation of interrelated elements in a material object or system (wikipedia). Material structures include man-made objects such as buildings and machines and natural objects such as biological organisms, minerals and chemicals.

Structure Design & Innovation

Structural innovation has been the focus of many design practices, especially in the field of generative design, growing design and mechanical engineering. Buckminster Fuller, the great inventor/ avant-guard of geodesic domes, had devoted his whole life and career in finding a universe structural solution for efficient architecture.

Most relevant structure types to material design and innovation is load-bearing structure. Buildings, aircraft, skeletons, anthills, beaver dams and salt domes are all examples of load-bearing structures. The results of construction are divided into buildings and non-building structures, and make up the infrastructure of a human society. Built structures are broadly divided by their varying design approaches and standards, into categories including building structures, architectural structures, civil engineering structures and mechanical structures. Load-bearing biological structures such as bones, teeth, shells, and tendons derive their strength from a multilevel hierarchy of structures employing biominerals and proteins, at the bottom of which are collagen fibrils.

MATERIAL EXPERIENCE

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According to Material Driven Design (MDD), “materials in products not only contribute to function but also to overall product experience: they gratify or disturb our senses, evoke associations, and elicit emotions and actions. ” (Experiential Characterisation Manual, Karana, 2019)

The notion of ‘materials experience’ emphasizes the role of materials as being simultaneously technical and experiential. Irrespective of the end result, we experience materials in products at four experiential levels, namely sensorial, interpretive, affective and performative.

Sensorial level: Our encounter with materials occurs at a sensorial level, through touch, vision, smell, sound and taste.

Interpretive level: The interpretive level concerns how we interpret and judge materials, that is, the situated meanings we ascribe to them after the initial sensorial encounter.

Affective level: We can be fascinated or disappointed by the qualities of a material embodied in a specific product. Such descriptions, such as surprising, which concern the emotions elicited by materials, fall under affective level.

Performative level: The performative level emphasizes the active role of materials in shaping our ways of doing. Performances and action elicited by materials, such as caressing, tweaking, fall under this category.

Each of these levels of materials experience is highly intertwined, suject-, object-, context-, and time-dependent attributes.

EXPERIENCING MATERIAL STRUCTURES

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It is argued here that material structure as an inherent part of material, can be perceived by people, as an important part of the material experience. Therefore, it is argued that the material structure can also be experienced on the four levels described by MDD. Due to the project scope on material structure as the main innovation, it is necessary to research what types of experience people can have with a certain material structure.

Material structure is normally associated with the technical performances. However, in the perspective of Material Driven Design, structures can also be experienced by people on the four levels: sensorial, interpretive, affectionate and performative. A designer makes structural innovation, not only to reach a certain function, but also might want to create a certain experience.

Before diving into designing root structure, a research is done into existing design practices in structural innovation as a benchmarking, for understanding material structure experience. This research provides a way to cluster material structures in the later tinkering process and experiential studies of Interwoven.

The main research questions in this section are:

- What are current examples of structural innovation in design?
- What is the purposes of these structures?
- How do designers present their structures to the audience/media?

As a result, 23 design cases have been studied, where structural innovation is the centre of design. Designers have different goals in structure innovation. Some want to make a strong structure to bear load with least material use, some want to make people think of a memory in the past, others want to elicit curiosity. The purposes of these structural innovations are clustered under technical and experiential levels according to MDD (figure [16]), in order to provide corresponding insights for later use.

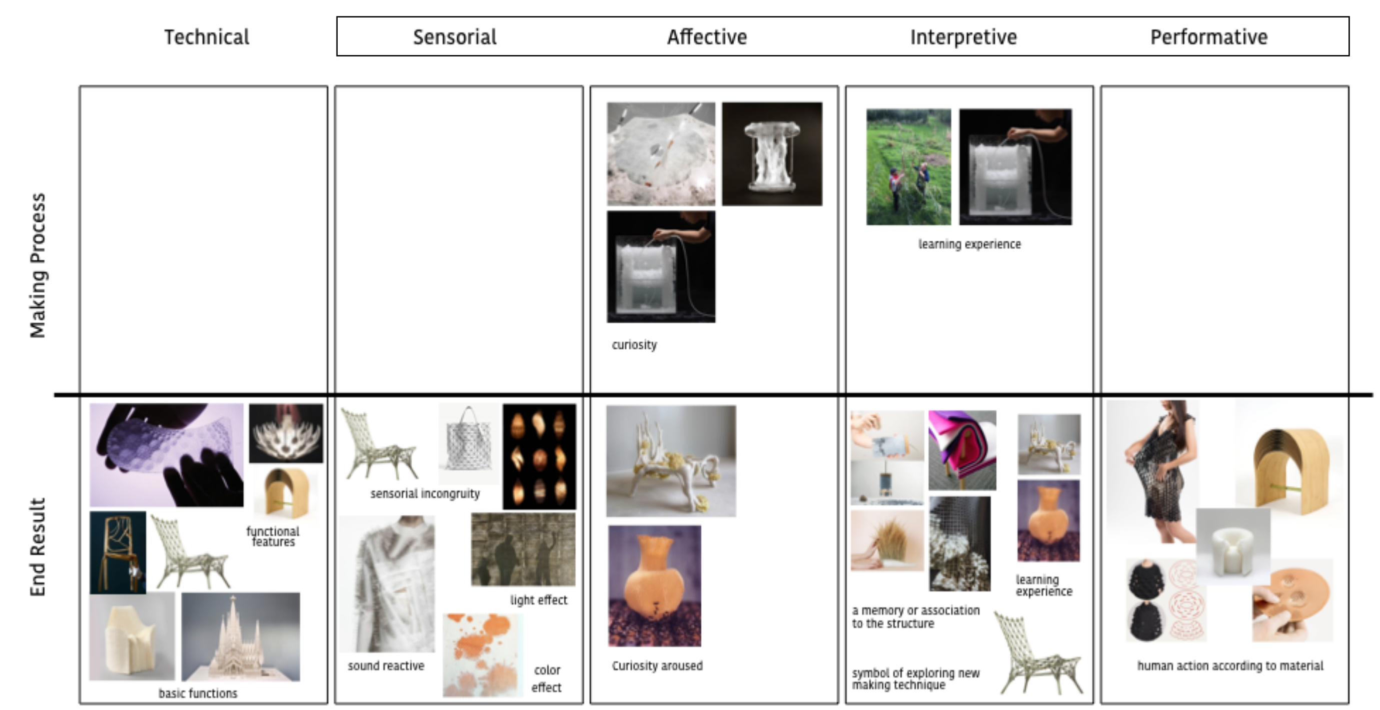

Figure [16]. Cluster of material structure experience

Structure for Techinical Purpose

Some structures are designed to perform a certain technical property, such as load-bearing and flexibility. In this case (figure [17]), the microstructures are changed by multi-material voxel printing technology, which enables design manipulation on microstructure level. Soft and hard materials are distributed in an arrangement in a product used for orthotic care with customisation opportunities.

Figure [17]. Voxel Harvest Project, adapted from https://www.designboom.com/readers/voxel-harvest-orthoic-care-11-01-2018/

In the case of Full Grown (figure [18]), a chair grown from a tree, the structure innovation lies in production process: growing a chair instead of cutting trees into pieces and re-connecting them again. The grown chair is claimed to be stronger because the material is fastened in one solid piece. Therefore, not only is it eco-friendly, but also technically satisfying and reasonable.

Figure [18]. Fullgrown Project. Adapted from fullgrown.co.uk

Structure for Experiential Purpose

Sensorial Level

On sensorial level, the cases show experiences created by material structures in visual and sensory incongruity aspects. Visually, some structures are aesthetical. These structures are usually used in lighting design, which emphasize visual attraction. Sensory incongruity means people think they know how something feels or smells before they actually touch or smell them. However, the real touching or smelling can be very different than their perceptions. Some material structures make people think the material is x, but when they really touch it, they feel surprised that the material is not x. For instance, the sensory incongruence created by the well-known Issey Miyake's bag design, makes people surprised when touching the product, because the softness is unexpected. This experience may evoke curiosity about how the bag is made, resulting in deisire and further exploration of the product.

Figure [19]. Issey Miyake Iconic Bag. Adapted from https://www.dezeen.com/2016/09/22/issey-miyake-bao-bao-bag-fashion-design-update/

Affective Level

On affective level, designers usually want to elicit curiosity from people. Sometimes even the structure is not practical for the purpose of the product it is imbeded, but this is not important. For instance, the Venus Chair (Figure. [20]) from Tokujin Yoshioka, only shows the process of salt crystalised into the shape of a chair with supporting structure in the middle. The product is not functional yet, but shown in a huge tank of water on exhibitions, which attract people to come closer and inspect the beauty of the process. The chair gains its appearance gradually over time, letting people see the forming process. The purpose of the design is to push the boundary of creativity through innovative production, instead of creating an end product.

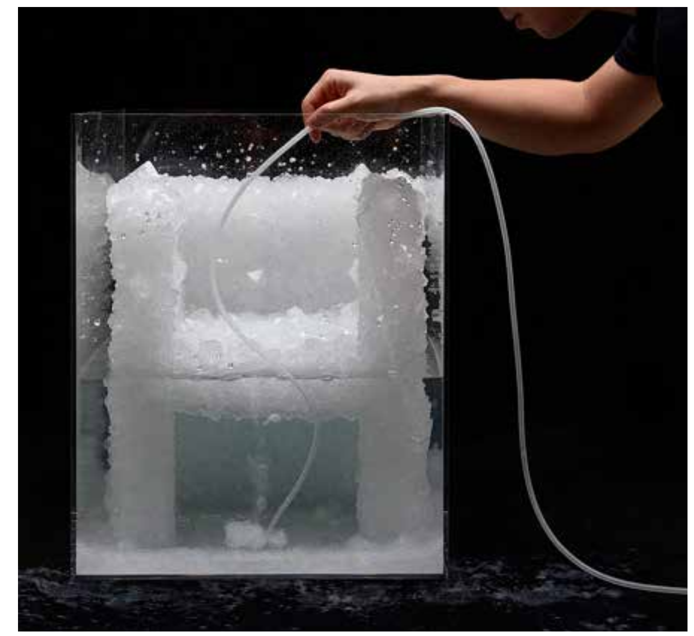

Figure [20]. Venus Chair. Adapted from https://www.core77.com/posts/11364/growing-furniture-the-venus-chair-by-tokujin-yoshioka-11364

Even if some designers show the end product, they don't expect it to be fully functional. Their purpose is more to raise curiosity from people of how it came into being, usually with a very strange and alien look. For instance the mycelium chair (Figure. [21]) by Klarenbeek & Dro, with mushrooms literally growing out of some parts, make people wonder why. This may raise a question towards whether the chair is a living creature or something produced.

Besides curiosity, there could also be other emotions: attractive, surprised, amusement, and disgusting, etc.

Figure [21]. Mycelium Chair, http://www.ericklarenbeek.com

Interpretive Level

The interpretive level concerns how people interpret and judge material structures, that is, the situated meanings they ascribe to them after the initial sensorial encounter. People might think a certain structure looks very strange or surprising because they have never seen it before or because they couldn't believe from the first sight it could bear load, etc. For these novel structures, there could be a learning process embeded in observing the structure or read/heard about why the structure is reasonable.

There might also be structures together with the product form that waken up people's memories. A chair imitating fliping the pages of a book, a fabric that makes people think of making pastas, a brush that reminds people of the rural field. (figure [22]) All these associations build personal connections with the product.

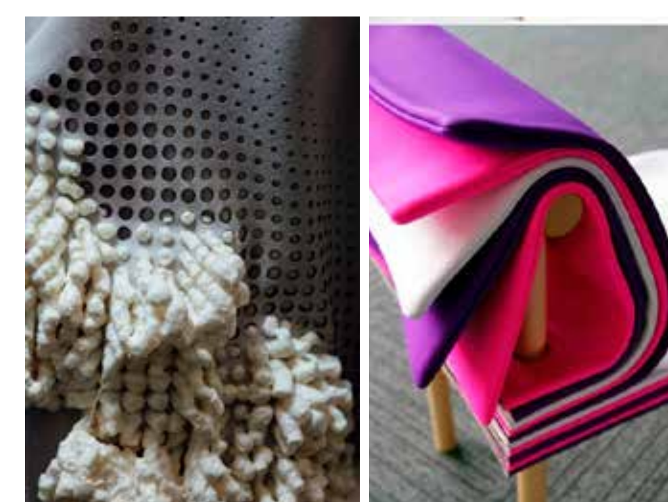

Figure [22]. Form & Structure that evoke certain memories in people. Pictures are from Pinterest.com

Figure [23]. Knotted Chair, 1996, by Marcel Wanders

Some structures have significant impact in design history, such as this Knotted Chair (1996) (figure [23]) designed by Marcel Wanders. Exploring new making techniques combining traditions and the new, it has become an icon and a point of reference for design and the years to follow. Part of the permanent collections of the Museum of Modern Art, New York, the V&A Museum, London and the Stedelijk Museum, Amsterdam, among others, the 'Knotted Chair' is a modern miracle of transparency, a highlight of the international design world and a sought after collector's item. (https://www.dezeen.com/2015/12/14/video-interview-marcel-wanders-knotted-chair-most-loved-movie/)

Performative Level

On this level, the focus is on what the structure makes people do to it. This is in relation with the term "Affordances" provided by a product interface. There is widespread agreement that affordances are possibilities for action offered to an animal by the environment, by the substances, surfaces, objects, and other living creatures that surround the animal (Barati, 2019).

For instance, the bamboo stool (figure [24]) with archs of different radius as sitting area may invite people to sit on with a bouncing action because the area looks elastic with this structure.

Figure [24]. Hangzhou Stool, https://www.designboom.com/design/hangzhou-stool/

Relevance to the Project

This research helps to connect material structure to material experience and to understand why people have certain reactions to a material structure in the experiential studies. It also helps to position some experiment samples in the categories under structure experiences and help tinkering process to be more structured.

CASE STUDY VISITING FULL GROWN

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Introduction

From the 23 cases, Full Grown is chosen as the one case study to go deeper due to its similarity with Interwoven. They both include designers focusing on controlling the shape in which the living system grows (the tree or the plant), thus affecting the structure of materials, but not the materials ingredients (Rognoli et al., 2015) (Camere & Karana, 2018).

Full Grown is a company, which grows furniture directly from trees. The author visited their growing field in Derbyshire in Britain and got introduced about their experiences in growing furniture. The visit aims at learning about how to design with growing material, how to alter plant structure for a functional human purpose.

In this section, photos during the visit will be shared, together with summaries about Full Grown's philosophy, production process, growing experiences, products and their doubts and challenges. What can be learnt from them and applied into this project?

Figure [25]. Grafting, pruning, aspliering and curing techniques used in Fullgrown chairs

Philosophy

Mass-produced wooden furniture is traditionally made by sawing a tree into appropriately sized and shaped pieces, which are then put together. However, cutting a tree to size of course leaves a lot of sawdust and other waste material. In order to cut out this waste material, and slashing the carbon footprint and energy consumption of furniture production, designer and artist Gavin Munro, decided to start growing furniture, using living trees. The project started in 2006 in the UK and has developed to a company called Full Grown. Based on an early idea of other people to create a living chair in 1904, Full Grown improved the techniques and aims at bringing it to mass-production.

Figure [26]. Modelling of the next prototype, being able to predict tree growth after 10 years of trial and error

The Production Process

The company has an orchard of 500 trees, including willow, oak, apple, hazel, cherry, ash and sycamore, which are grown in the shapes of tables, chairs and lamps. The process starts by training and pruning young tree branches as they grow over specially made formers. At certain points the branches are grafted together so that the object grows in to one solid piece. After it's grown into the expected shape, people continue to care for and nurture the tree, while it thickens and matures, before harvesting it in the Winter and then letting it season and dry. It's then a matter of planning and finishing to show off the wood and grain inside. The process is described by the company as Zen 3D printing-an organic way that uses air, soil and sunshine as its source materials very slowly. Depending on the type of the tree, it usually takes 4-8 years to grow a functional chair. However, the carbon footprint and the energy consumption is 75 percent lower compared to normal furniture manufacture.

They are only using old agricultural techniques such as pruning, curing, aspliering and grafting (figure [25]) to fulfill such complicated growth. Through trial and error, they have found a way to follow the natural growth of branches by observing where they want to grow and then slightly steer the growing towards what they want, instead of forcing branches to do so.

The End Product

Products include chair, table and light-shade. The first chair prototype (figure 16) was shown on Ted Talk in 2014. However, products are still in experiment phase. Followed by two earlier generations of experiments starting in 2012, the third generation of chair experiments began in 2015. Each piece is unique. Speaking of product quality, the chairs are expected to be not just fully functional and ergonomic but also grown, grafted and fastened into one solid piece, no joints that only ever loosen over time which could last for centuries. The company hopes and trusts that this will eventually become an improvement on current methods.

Currently, there are two options to reserve the products: online commission and applying to be waiting-list customer. Each year, only 10 chairs, 15 lighting and 5 tables are available. The current commissions for chairs are pre-ordered up 2029. Figure on the left side shows their most recent model - a solid piece of chair.

Doubts and Challenges

The most doubted plastic molds have been changed into steel frames that are more sustainable. Another challenge is that the production process is very time consuming. Not just because of the pruning and grafting of 3000 trees at the right time, but also the patience needed while waiting for the final outcome. Furthermore, since the production is completely open-air, the biggest challenges of the production lies in pest and diseases like any other crop. In order to reduce the risk, the company has worked with natural means to tackle the problem, such as introducing wasps and birds that eat the pests to create a healthy ecosystem. Finally, the company is also seeking for financial help, for the maintenance costs of the whole system.

Relevance to the Project

Apparently, Full Grown and Interwoven share a similar approach: they both use tools and techniques to change natural growth into something human beings are interested in. Nevertheless, Full Grown takes way longer to harvest than Interwoven (several years vs. less than 2 weeks). The growing time of roots are way shorter, which is an advantage.

Traditional holticultural methods are helpful to take reference in manipulating growth.

It is learnt that experiments will lead to ability to predictable growth (figure [26]). This insight leads to the summary of root behaviour as an important result of this project.

It is also learnt that **EXPERIENCING FULL GROWN CHAIR IS WAY MORE THAN ITS FUNCTIONALITY**. Listening to Chris (one of the helpers at Full Grown field) talking about their ten years' trial and error process and the perfection they are seeking, one could experience at the same time: respect, touched, curiosity, etc. And these experiences are more at affective and interpretive level. Therefore, except from making the material functional, it is equally important to present the trial and error in designing the material and the narratives around it. The material concept itself, could express the philosophy behind it.

3

Understanding Root Structure

This chapter introduces the process of understanding root structure, by looking at its biological origins, how people experience Interwoven, and technical properties.

BIOLOGY OF ROOTS

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Interwoven is a natural material developed from roots. The root is a non-leaf organ of the plant's body, typically growing downward into earth. The primary functions of the roots are to anchor the plant, absorb water and dissolved minerals, conduct nutrients to the stem, and store food supply. In this section, background knowledge of root biology related to root composition, root growth and root intelligence will be presented.

Types of Root System

There are two main types of root systems. Monocots (flowering plants whose seeds typically contain only one embryonic leaf) have a fibrous root system, while dicots (flowering plants with two embryonic leaves) have a taproot system (wikipedia, monocotyledon) (Figure [27]). Upon the germination of the seed, a taproot system's primary root appears. As it grows down vertically attaching the plant, secondary lateral roots arise. In contrast, a fibrous root system is located closer to the soil surface where it forms a dense network of roots of roughly equal diameter. The network is formed by many branching roots developing from the stem base. Interwoven is using oat - a monocot, which has a fibrous root system, causing even distribution of single roots. (Smith & De Smet, 2012)

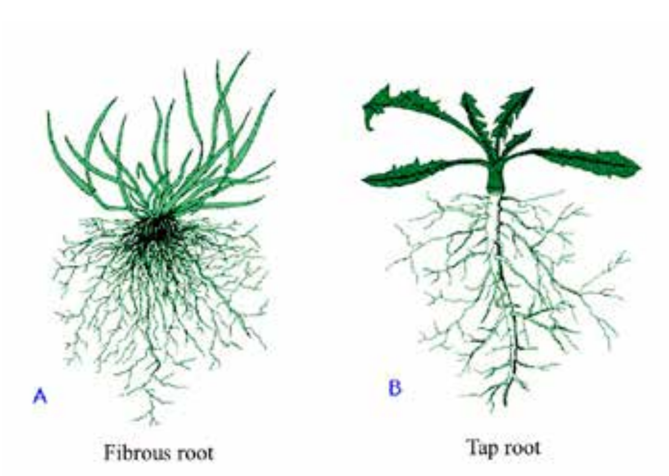

Figure [27]. Comparison of fibrous root and tap root

Monocot Root Anatomy

Upon dissection, the arrangement of the primary tissues in a root (from outermost to innermost) is epidermis, endodermis, cortex, stele (vascular cylinder), and pericycle. ("Characteristics of Monocotyledonous Roots | Botany", n.d.)

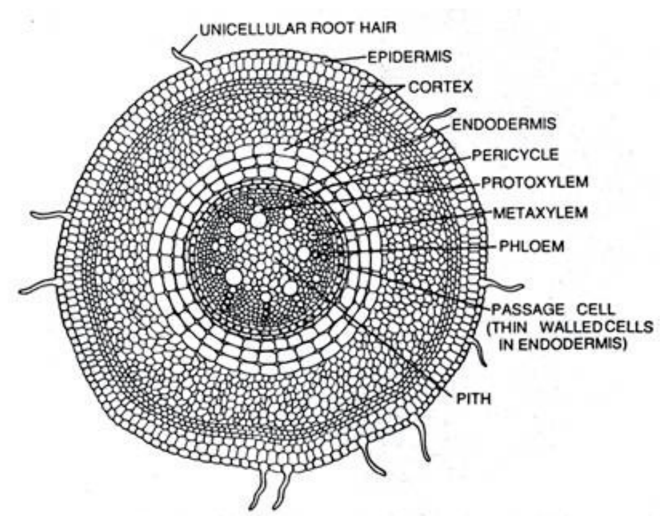

Figure [28]. Monocot root anatomy, cross section of root of Commelina

- The epidermis: is the protective covering for the root, composed of a thin wall of cells which generate root hairs.
- The endodermis: the inner boundary of the cortex, thick as a one cell layer, and responsible for the movement of the water and minerals into the xylem and phloem. The endodermis has a band called the Casparian strip which prevents leakage of nutrients to the outer layers of the root.
- The cortex: made out of parenchyma cells is functioning as a storage of food in the form of starch. Also, it aids in respiration as cells bear intercellular spaces to support the gas exchange.
- Stele (or vascular cylinder): a central cylinder of the root made out of xylem and phloem
- The pericycle: a layer of cells inside the endodermis. It is a point of origin for the lateral roots.

Root Growth and Development

Root growth begins with seed germination. When a seed sprouts, the first structure to emerge is a root. When the plant embryo emerges from the seed, the radicle of the embryo forms the root system.

There are several developmental and morphological areas of roots which can be divided into: a region of cell division, a region of cell elongation and a region of maturation as shown in figure [29]. All three regions are in approximately the first centimeter of the root tip.

Roots grow from their tips, by dividing cells and elongating them constantly. The cell dividing area is called apical meristem. As it is easily damaged while the root is making its way through the soil, there is a protective area at the tip of the root called a root cap (Figure [29]).

During the first phase of cell division, roots are approximately 1 mm in length. Apical meristem (region of cell division) is developed. As the root develops, some of the divided cells are being added to the protective cap while most of them are joined into the region of elongation.

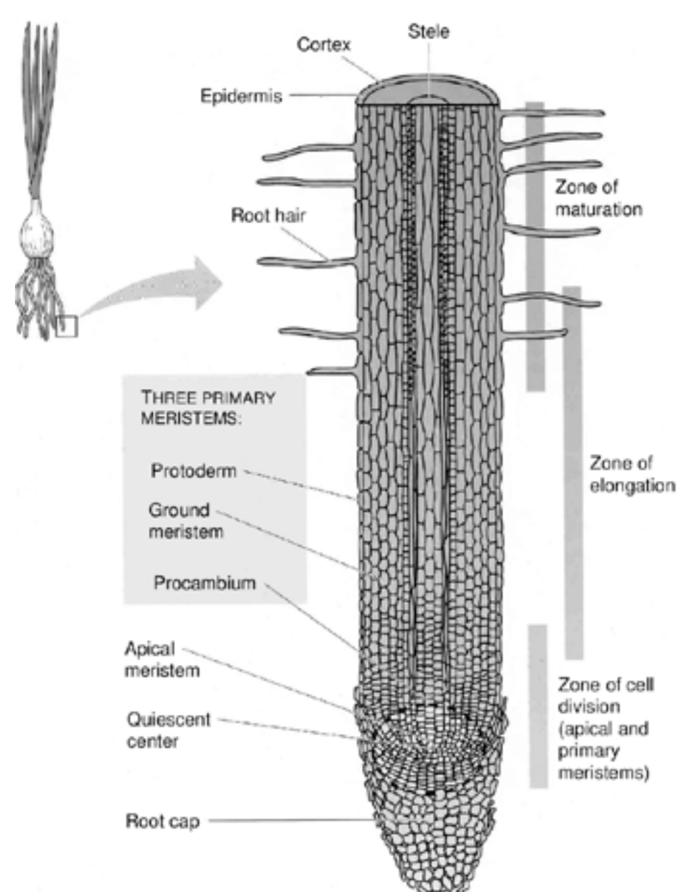

Figure [29]. Vertical cross section of root. Adapted from https://lapakonlineindonesia.id/root-tip-root-apical-meristem-protoderm-procambium.html

The region of cell elongation is following the development of roots at approximately ~2 mm in length. This is where the newly-formed cells increase in length, thereby lengthening the root. As cells elongate, functional xylem (transport tissue of water and nutrients from roots to stems leaves) starts to develop. At this stage phloem (the living tissue that transports the sugar sucrose made during photosynthesis to parts of the plant where it is needed) matures.

Root hair will grow from the region of maturation where the root cells differentiate into specialised cell types. This region is about 2 mm. Root hairs are produced, xylem and phloem are both matured and present. (Hartnell, 2018 and CAERT and Campbell, root anatomy, n.d)

Root Intelligence

In an interview with professor Hans de Kroon in Plant Ecology from Radboud University, it is known that oats are chosen to fulfill the textile making needs because they have very fine roots and thus can show very precise patterns. Oats also have other merits: fast growth and crowding possibility. Roots are always looking for their living space underground and fill it up. The roots weave themselves together by lying one beside each other, up and down, like ropes.

Roots' ability to find their way is related to the so-called "intelligence of plant", which is still a controversial topic. However, in observable experiments, some scientists have proved many comparable intelligence to humans. For instance, their ability to perceive and respond to environment.

Root perception and response to environment is presented thoroughly in a publication by Trewavas in 2003. "Roots are able to sense humidity gradients and thus also construct a three-dimensional environmental perspective (Takahashi and Scott, 1993). Increased root branching in soil patches rich in nitrate or phosphate indicate a similar ability in environmental perception (Drew et al., 1973). Roots will also take avoidance action when near others (Aphalo and Ballare, 1995). These data, and others, have led to the concept that plants actively forage resources from their environment (Hutchings and deKroon, 1994) using assessment mechanisms similar to those of animals. Red light, calcium, touch, moisture, oxygen, temperature, ethylene and auxin have all been reported to modify gravitropic bending, illustrating the common observation that physiological phenomena are integrated responses resulting from many environmental influences (Trewavas, 1992)."

Factors for root structure

The most relevant environmental factors influencing Interwoven in its growing process are watering, nutrients and obstacles:

- **Watering and Nutrients**: The growth of the roots are closely linked with watering. Over-watering will cause shallow roots while proper watering will facilitate the roots to grow healthily and deeply to anchor into the ground.
- **Gravity**: Roots grow towards the direction of water gradience, which is in the normal case direction of gravity.
- **Obstacles**: The roots find their way through the soil in a similar way to a person groping through the dark. If they come across some obstacles, they feel their way around it until they come to a point where they can grow again. In experiments done by Cornell University, (figure [30] & [31]), roots show path finding signs in different slopes.

These principles will help the design of the templates that help form a healthy root system and also navigate roots into a certain structure underground.

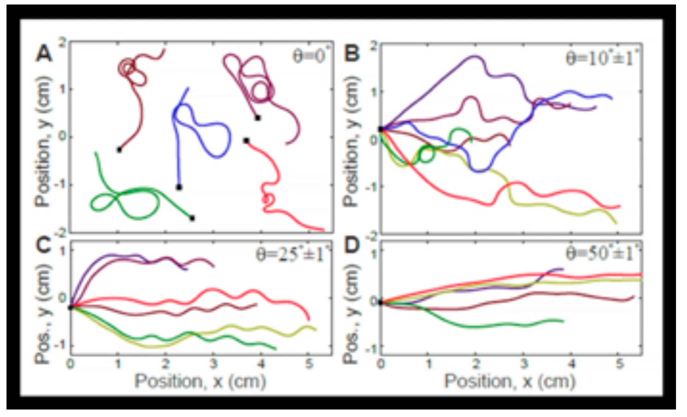

Figure [30]. Root growing traces related to degree of the growing surface. Adapted from: How do plant roots find the quickest way down? (Cornell University)

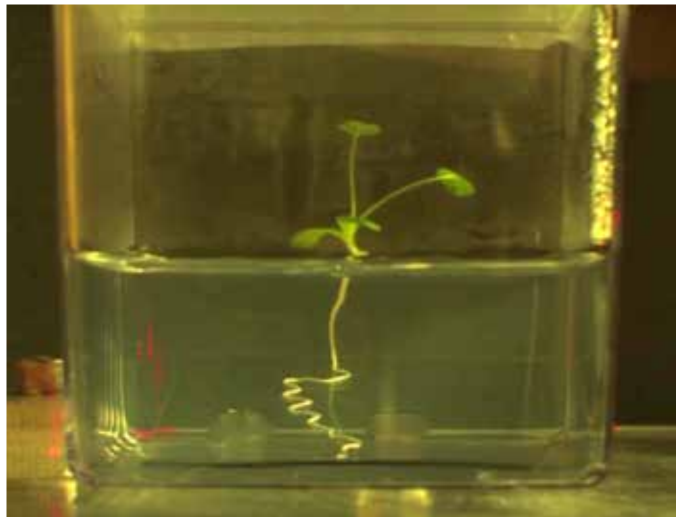

Figure [31]. Root growing traces on a slope. Adapted from: How do plant roots find the quickest way down? (Cornell University)

Factors that influence Root Strength

The root strength mentioned here is mainly about tensile strength, which is provided mainly by root stele and cellulose content (Hathaway & Penny, 1975).

To increase the tensile strength means modifying root anatomy by biological means or increasing root density by cultivation means, of which cultivation means are more accessible by material developers. The cultivation factors that will increase root strength include (Mackenzie, 2018):

- **Plant Type**: Root strength varies by plant types. Usually, plants with higher drought tolerance have stronger roots. Mix of different types of roots may also increase each other's strengths. (Interview with Hans de Kroon, 2019)
- **Drought**: Drought helps plants to develop a bigger root system and stronger roots. The growing speed and strength will both increase in such conditions.
- **Fertilizer**: Commercial fertilizers typically display an N-P-K ratio that indicates the percentage of nitrogen, phosphorus and potassium, respectively. A ratio of 3-20-20, that contains 3 percent nitrogen, 20 percent phosphorus and 20 percent potassium encourages roots to grow strong and healthy. Keep the nitrogen content low, as it promotes leggy green growth at the expense of rooting.
- **Hormone**: Vitamin B1 and plant hormones called auxins are considered to be root stimulators.

Relevance for the Project

Roots behaviour differs in different growing space. Designing root structure becomes designing the space roots grow in, together with the whole set of growing conditions.

Understanding the growing organism from biological perspective is crucial in human intervention into the growing process. Especially, for the collaboration between designers and scientists, cultivation methods play a significant role in further altering root properties.

Knowledge of root intelligence helps to manipulate the growing conditions and make predictions of root behaviour accordingly.

MAKING OF INTERWOVEN

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An interview with Diana provided practical insights into the growing conditions, ingredients and activities required for the production process, which helped the designers create a visual diagram on how the material is fabricated as depicted in Figure [32].

The project is under an NDA agreement, therefore some aspects of the production process can not be disclosed in the report. However the 7 steps depicted below are illustrated. To summarize, a mould is created and soil is on top of the mould; oat seeds are placed into the soil, water added and artificial pink (red & blue) LED growing light provided. A timer must be used to simulate the daylight hours and water must be provided regularly to the soil. The plants fibrous root system will grow through the soil in its search for nutrients and then begins to channel itself into the patterns of the mould, weaving itself together into a single material. The root textile is then cut from the soil and left to dry on one of the grids.

The whole process is manipulatable in many aspects, such as mould designing, mould material, growing conditions and co-creation structure, to create different material results.

Figure [32]. Simplified process for making Interwoven

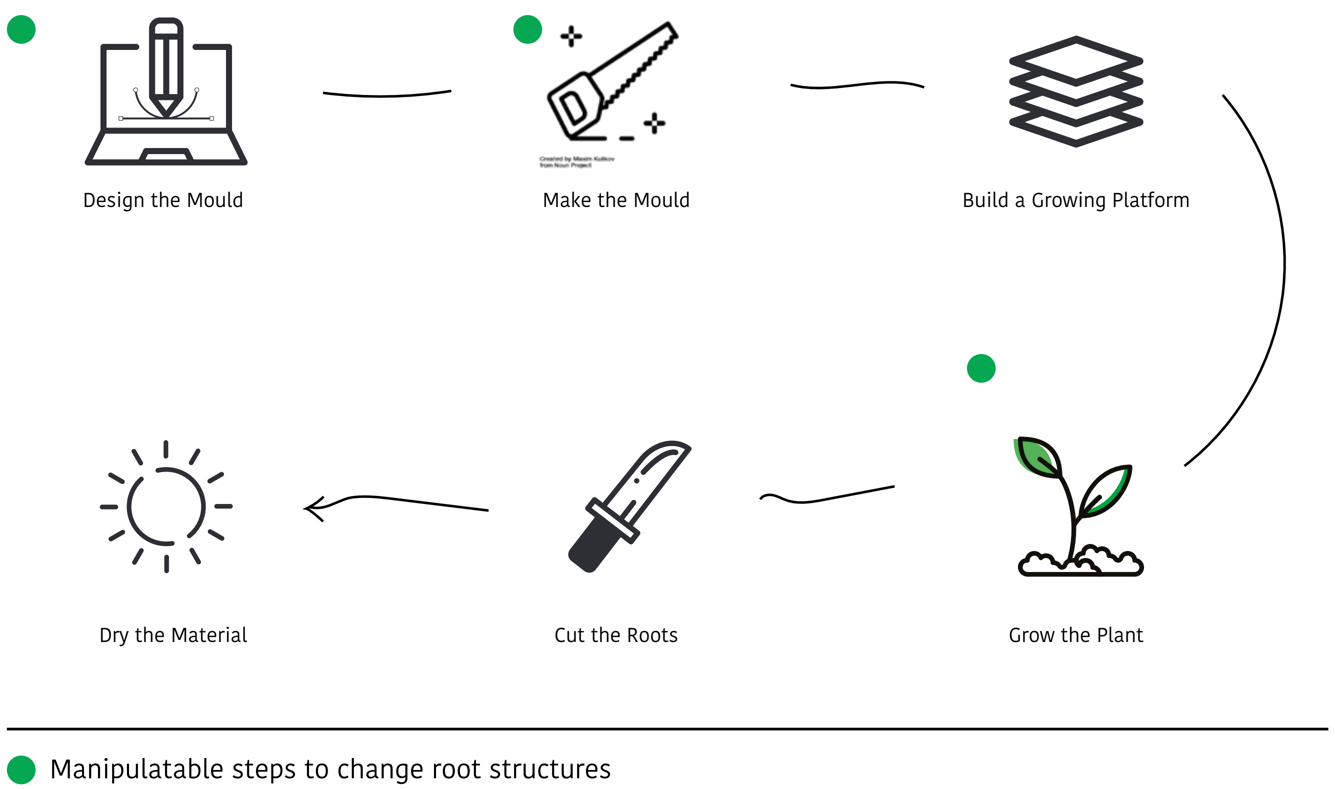

Figure [33]. Diana Scherer in her studio in Amsterdam

Figure [34]. Samples for tensile test

TECHNICAL CHARACTERISATION -

Introduction

If the material is fully developed, technical datasheets concerning its mechanical and technical properties and possible manufacturing processes to form the material can be easily accessed through material suppliers, or online material databases (e.g., CES, matweb, material, etc.). On the other hand, if the material is not fully developed, in this case the Interwoven material, the technical characterization should be achieved through the process of MDD. This to understand its inherent qualities, its constraints, and its opportunities when applied in products.

When the technical characterization of the material is completed, the following questions should be answered:

- What are the main technical properties of the material structure?
- What are the constraints/opportunities of the material structure?

At this stage of the project, strength and structure are most relevant technical aspects that need to be investigated. Therefore, a tensile test and microscopic examination have been conducted.

Material Composition

Ideally, current textile samples are supposed to only consist of dried oat roots. However, due to the current growing techniques, some soils/ coco fibres as growing media inevitably adhere, which makes some samples look "dirty". If controlled well, the material should be pure roots. Figure [34] shows this kind of pure root textile sample with two kinds of patterns: voronoi and geometrical. They are about 0.3mm thick.

Tensile Test

Strength is a measure of the stress that can be applied to a material before it permanently deforms (yield strength) or breaks (tensile strength). If the applied stress is less than the yield strength, the material returns to its original shape when the stress is removed. If the applied stress exceeds the yield strength, plastic or permanent deformation occurs, and the material can no longer return to its original shape once the load is removed. If the applied force exceeds the tensile strength, the material will break permanently. (https://www.thefabricator.com/article/metalsmaterials/the-differences-between-stiffness-and-strength-in-metal)

Since Interwoven is seen as a textile at the current stage, the fragility mainly lies in the fact that it breaks easily under a tensile force. How fragile is it then? A tensile test is needed to quantify it and compare to existing data of popular textile materials like cotton of hemp.

The tensile test helps to understand the following questions:

- What is the tensile strength of the current samples?
- How is it different from existing data of common fabrics like cotton fabric?
- Does it make a difference if thickness and density increase?

Test Method
The test takes reference at Standard ASTM D5034-09 (Standard Test Method for Breaking Strength and Elongation of Textile Fabrics). However, due to the foreseen fragility of Interwoven, the test method is adjusted to suit the available materials. The dimension of test specimen is adjusted to 35mm wide by 110mm long. The elongation rate is set at 2mm/min to ensure slower change in load. The test is to give a basic idea of load bearing ability the current material. Therefore the differences from the standard is accepted.

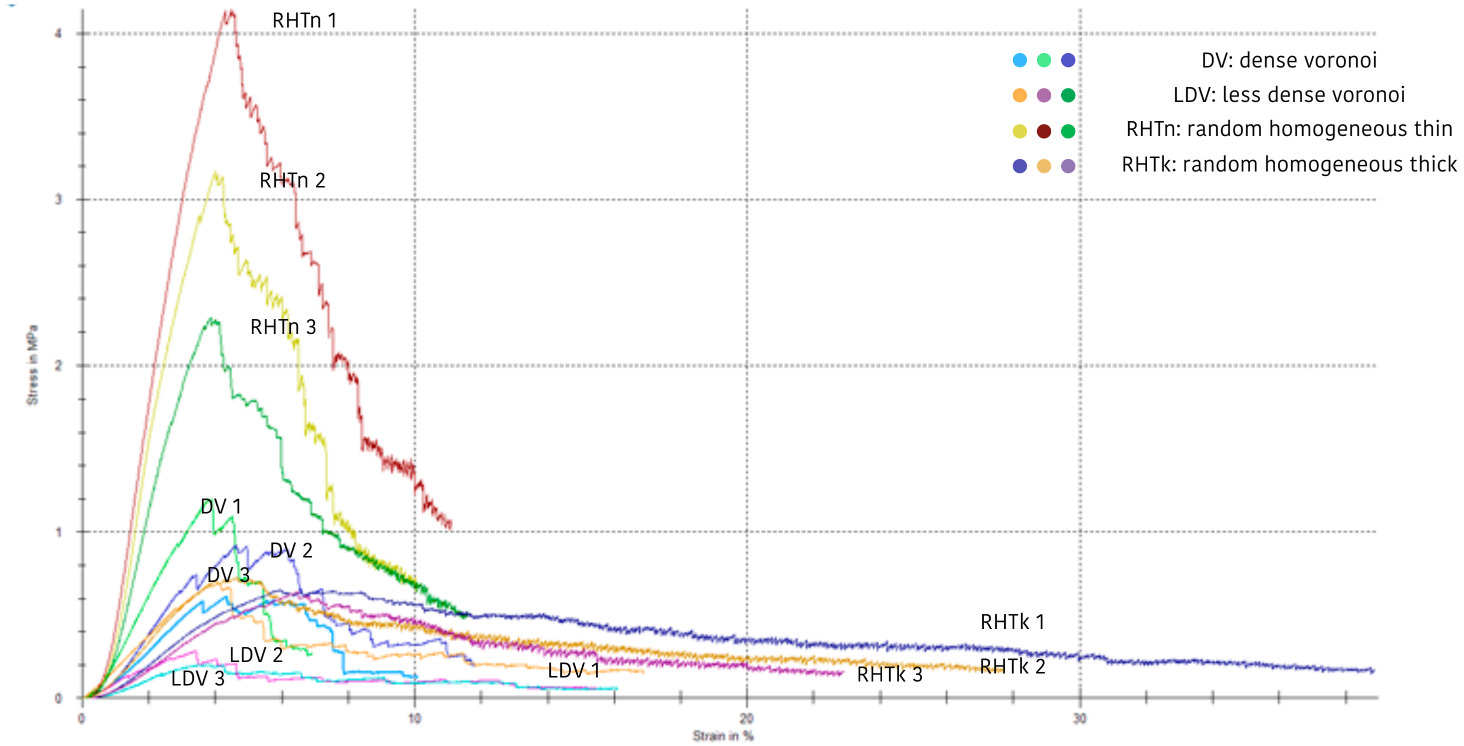

Figure [35]. Stress-strain curves of tested samples

Samples

Four groups of materials are chosen for the test: a dense voronoi pattern, a less dense voronoi pattern, a random homogenous arrangement and a thicker piece of random homogenous arrangement. Each group has 3 samples, cut in strips with a surface of 35 x 110mm from a larger piece of textile. Admittedly, the 3 samples of the same group are not identical, because of the randomness of grown results; however, they reflect the same way of pattern arrangements of the roots. Prior to testing, the samples were accurately measured (weight, length, width and thickness) to ensure a proper comparison. This figure [34] shows the samples before testing.

Results

The tested specimens show varied tensile strength (figure [35]). Amongst all, The test results show that the average tensile strength of a dense (hole size 5mm by 40mm) voronoi Interwoven is around 1.2MPa, a less dense voronoi (hole size 10mm by 40mm) Interwoven is around 0.4MPa (the smallest), a thin piece of random homogeneous pattern is around 3.2MPa (the largest), a thicker piece of random homogeneous pattern is around 0.6MPa.

Discussions

Low strength: in comparison to the tensile strength of cotton fabric: 550MPa (the data is collected from researchgate.com: Preparation and properties of multi-functional cotton fabric treated by gallnut extract), the current textile sample is dramatically weaker than cotton fabric, which makes it very difficult to apply as a design material without improvement.

Root density influences strength: the dense voronoi pattern samples are stronger than less dense voronoi samples, but the thicker random homogeneous samples are not stronger than the thinner ones. While higher density of pattern might mean more roots contributing to resistance of tensile force,if the samples are not from the same batch of growing, other conditions such as seed numbers and nutrients might influence the strength. Additionally, a density test is done to check if the thin and thick random homogeneous samples have similar root density. As a result, the thin piece has a density of 0.39g/mm3, while the thicker piece has 0.29g/mm3. Therefore, even though some samples are thicker, the root density might be lower, which makes the tensile strength lower.

Thick pieces are more ductile: the curves are all zigzag after the peak force. This could be explained by the fact that roots break one by one, but not at the same time. Especially, the thick pieces have very slowly dropping zigzag curves, which means the ductility is high for more durable use.

Microscopic Examination

Microscopic Examination is to view how roots are connected or “woven” as is previously understood. This test is using a stereomicroscope (an optical microscope variant designed for low magnification observation of a sample). The magnification is 10 times.

- How do roots look like under the microscope?
- How do roots connect to each other?
- How does the fracture from tensile test look like?
- What is the microstructure of roots?

Method

Both intact and broken samples after tensile test are brought to examed under microscopes. Intact samples are under stereomicroscope with a scale bar on the photo, while broken samples are only observed without a scale bar.

Results

From the microscopic images, it can be observed that each dry root is around 1/3mm wide, with a root tip of around 2/3mm wide (figure [37]). Massive root hairs - the reflective fine white filaments are intertwined together, forming a web that holds the roots (figure [38]). Roots show random positioning arrangements in a bunches: they are curled randomly and crossing through each other randomly, as is observed. That can be explained by the fact that roots are looking for their way in a limited space and wherever there is space, they go into. The root tips are clearly visible and stay where they were when growth was stopped. The fractures mainly happen at root itself.

Discussions

An important insight from the microscopic examination is that root hairs are very developed and intertwined in-between roots. Some roots break so there is fracture, but also some roots slipped from each other, causing the failure in tensile resistance (figure[36]). The root hairs

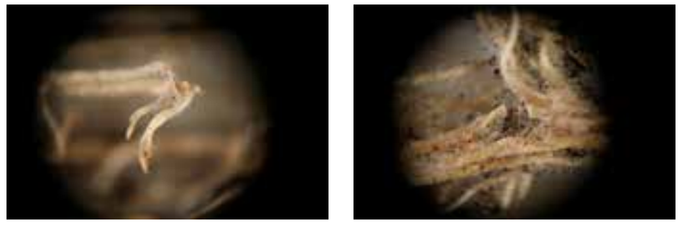

Figure [36]. left: some roots slipped from others during the tensile test; right: some roots broke during the tensile test

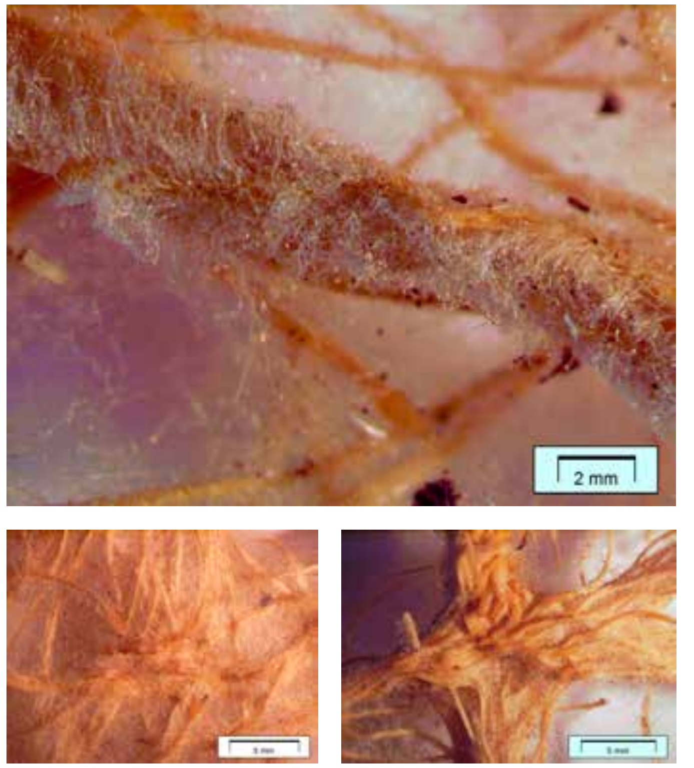

Figure [37]. a. a bunch of roots intertwined together; b. random homogenenous arrangement; c. a node in a voronoi pattarn sample

Figure [38]. massive root hairs connceting roots and forming a web

Figure [39]. fractures on the surface of the random homogeneous thick sample are crucial to help roots stick together and increase friction. Their contribution to strength is visible, which should be taken into consideration in altering root structures.

The number of roots on one cross-section might be the main influential factor of strength. The root hair bind the roots, but may not provide strength on the tensile direction.

Insights
The main insights from technical characterisation of the current structure are fragility and the connectivity of root hairs. The fragility is definitely the biggest constraint, while the connectivity of root hairs can be utilised to optimise the material structure. For instance, increasing the complexity of the root web, etc. Since root density has much more influence on strength than patterns, pattern design will not be the main strategy to increase strength. And since the roots fail at different times, it could be assumed that the material ductility should be considered in its application. That means that even when some roots break, others can still support the function.

EXPERIENTIAL CHARACTERISATION

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Introduction

In design, a holistic approach to materials is adopted which requires the characterization of materials for their experiential qualities, alongside the technical understanding (Camera & Karana, 2018). This section introduces experiential characterisation of a textile sample borrowed from Diana Scherer, in order to understand how people experience Interwovne and prepare for a reference for later developed samples. Such an understanding of materials does not only provide guidance on how people are likely to experience a particular material in future product applications and how to improve materials accordingly for commercial success, but it also inspires designers and material developers to come up with innovative material and product ideas (Camera & Karana, 2018).

Materials Experience' emphasizes the active role of materials in shaping the ways people interact and experience products at four experiential levels: (1) sensorial level (e.g. we think the material is heavy or rough),(2) interpretive level (e.g. we think it is modern or high-quality), (3) affective level (e.g. we feel fascinated or surprised by the material), (4) performative level (e.g. the material makes us tweak it or caress it). These levels articulate an operational understanding of materials experience, categorizing different experiential qualities that can be elicited by materials. Nevertheless, these levels of materials experience are highly intertwined and experienced as a whole, influenced by each other and by other factors such as time and context of use (Karana, Pedgley & Rognoli, 2014; Giaccardi & Karana, 2015).

In understanding the current sample of Interwoven, these questions are concerned:

- How do people interact/behave with the material structure intuitively?
- What are the sensorial properties of the material as a whole?
- What emotions does the material evoke?
- What meanings are associated with the current sample?
- What memory does this material relate to? And why?
- Where and for how long would people imagine this material being used?
- What are the most pleasant and unpleasant qualities of the material?
- What is the most unique quality of the material?

In order to facilitate the test procedure, a characterisation tool called Ma2E4 (Camere & Karana, 2018) is used and adapted to suit Interwoven. To answer these questions, the experiential characterization is conducted with 10 participants from varied study and cultural backgrounds from the university. These studies will be introduced and shortly summarised in the next section.

Participants

To obtain a diverse perspective on the current sample, 10 master students from Delft University of Technology have been invited to perform the experiential study. Their study backgrounds are Design for Interaction, Strategic Product Design, Integrated Product Design, Geomatics, Architecture, Electronic Engineering, Dutch Language, Visual Design. Their cultural backgrounds are Chinese, Indian, Singaporian, Dutch, Italian and Turkish. All participants except for one are non-informed of the material origin - plant roots in advance, so their intuitive reactions have been appreciated.

The Stimuli

Figure [40]. a flat textile sample borrowed from Diana Scherer

Characterisation Tool

A characterisation tool has been designed based on [Ma2E4] (Camera & Karana, 2018). The tool is a foldable questionnaire which includes characterisation of 4 levels of material experience. The purpose is to unfold each level of experience at one time and provide an overview of the understanding of the sample in the end for the participant to reflect on.

For the experiential characterisation of the current textile sample, the tool has been redesigned to fit Interwoven better, the considerations are as follows:

- The performative level is aided only by a camera that records participants' hand movement, instead of observing and choosing from a series of actions which are very limited in describing more complex movements. In this way, the videotapes can be analysed afterwards and the facilitator is able to focus on an open conversation with participants, which helps to understand participants' interaction with the material sample.

- New emotions are added to the options, because they are assumed to be possibly relevant to Interwoven. These emotions are adopted from 700+ Product Emotions (Desmet, 2018).

- Interpretive vocabulary has been enlarged, based on a previous research of Elvin Karana, resulting in 687 collected material descriptions. 3 students from different design backgrounds (Design for Interaction, Strategic Product Design and Integrated Product Design) have been invited to choose the descriptions they are interested according to Interwoven. The choices have been then selected again by the author for a manageable amount of 60 words in the test. Additionally, it is suggested by the research of [Ma2E4] tool that designers should choose their own set of visuals for each meaning. Therefore, 3 images depicting each descriptive word are selected, presented on a card together with the word.

- One section is added to the characterisation: the context of use and time period of use, as is argued by Karana: a variety of factors, including form and function, user characteristics, and context of use, can be influential in our experiences of products (Karana, 2009). Therefore in this study, participants are also invited to imagine where this material will be used. Besides the context of use, participants are also requested to mention for how long the material would be used in the context they imagine. This is to understand how fragility influences their understanding of the material longevity, and their willingness to accept this fragility.

The tool includes two A3 pages and three sets of cards (figure [42]). On the first A3 page, sensorial, affective and interpretive levels are asked, with the help of cardsets of emotion words and interpretive words. The second page provides space for participants to group time and context of use. The right page shows an example. An example of the tool filled in by a participant is shown in Appendix C.

Figure [41]. Test set-up for experiential characterisation

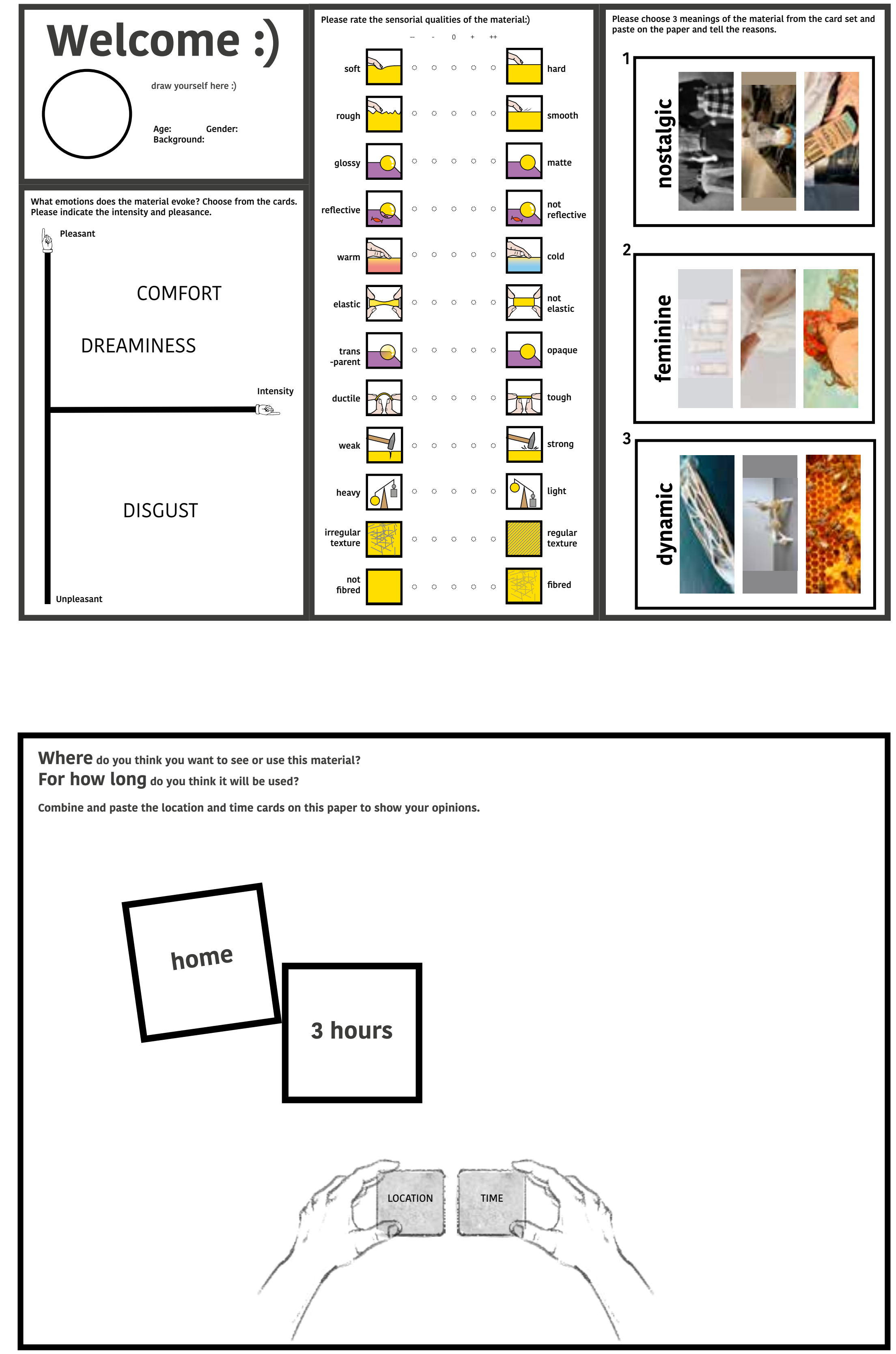

Figure [42]. Modified characterisation tool for experiential studies

Process

Each participant has been invited for a one-hour session separately. The whole process is audio-taped.

Firstly, they are presented with the material and requested to play in their hands (figure [43], performative level), while speaking aloud what they think and associate immediately. It is emphasized that there's no right or wrong about their opinions. The whole process is recorded with a camera.

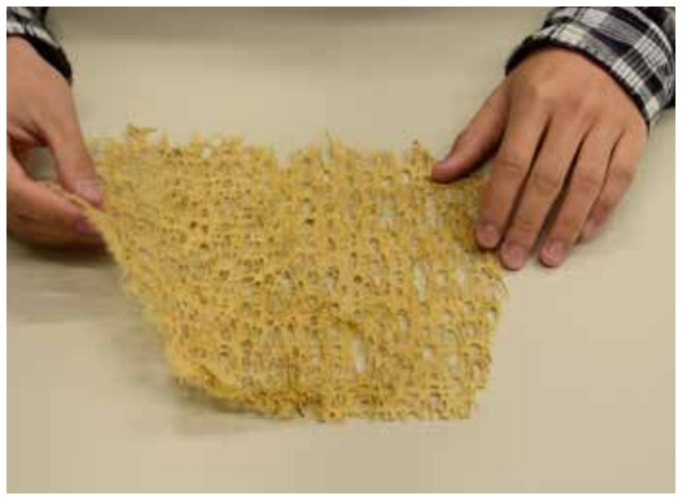

Figure [43]. First step: to play with the material

Afterwards, they should fill in the characterisation tool, in the sequence of sensorial, affective, interpretive and contextual/temporal level and explain their choices. During the process, the facilitator can ask questions according to the answer and get timely feedback.

Figure [44]. Second step: filling in the characterisation tool. One participant was choosing from interpretive cardset he was provided

And then, they are asked to imagine where and for how long the material can be used, and present their opinions by combining cards with context names and time periods on a sheet of A3 paper. They can choose as many as they want to, and explain why. In the end, participants are asked to reflect on the material qualities overall: what are the most pleasant, unpleasant and unique qualities of the material? And what memory do they associate with the material?

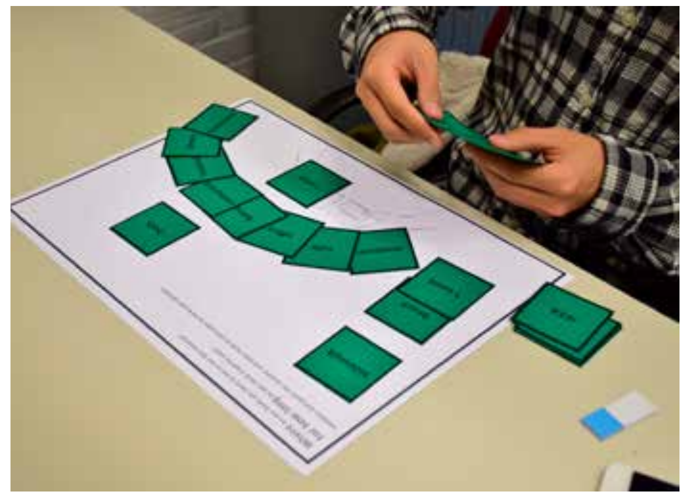

Figure [45]. Modified characterisation tool for experiential studies

Results

The analysis of the data is qualitative, due to the limited number of participants. The characterisation tool, facilitator's notes, video and audio tapes provide rich information for the analysis and have all been taken into consideration.

Performative Level

Please see the trimmed gifs of performances on this link: https://vimeo.com/353386618. Thumnails are shown in figure [46]. The interactions are: bending, folding, rustling, breaking, rolling, seeing through, drawing, pressing, rubbling, feeling both sides, smelling, stroking, stretching, tapping and wrecking. The most common interactions are stretching, stroking, tapping and folding. The quality of stroking and tapping are tender and slow, while stretching and folding are very tentative and careful.

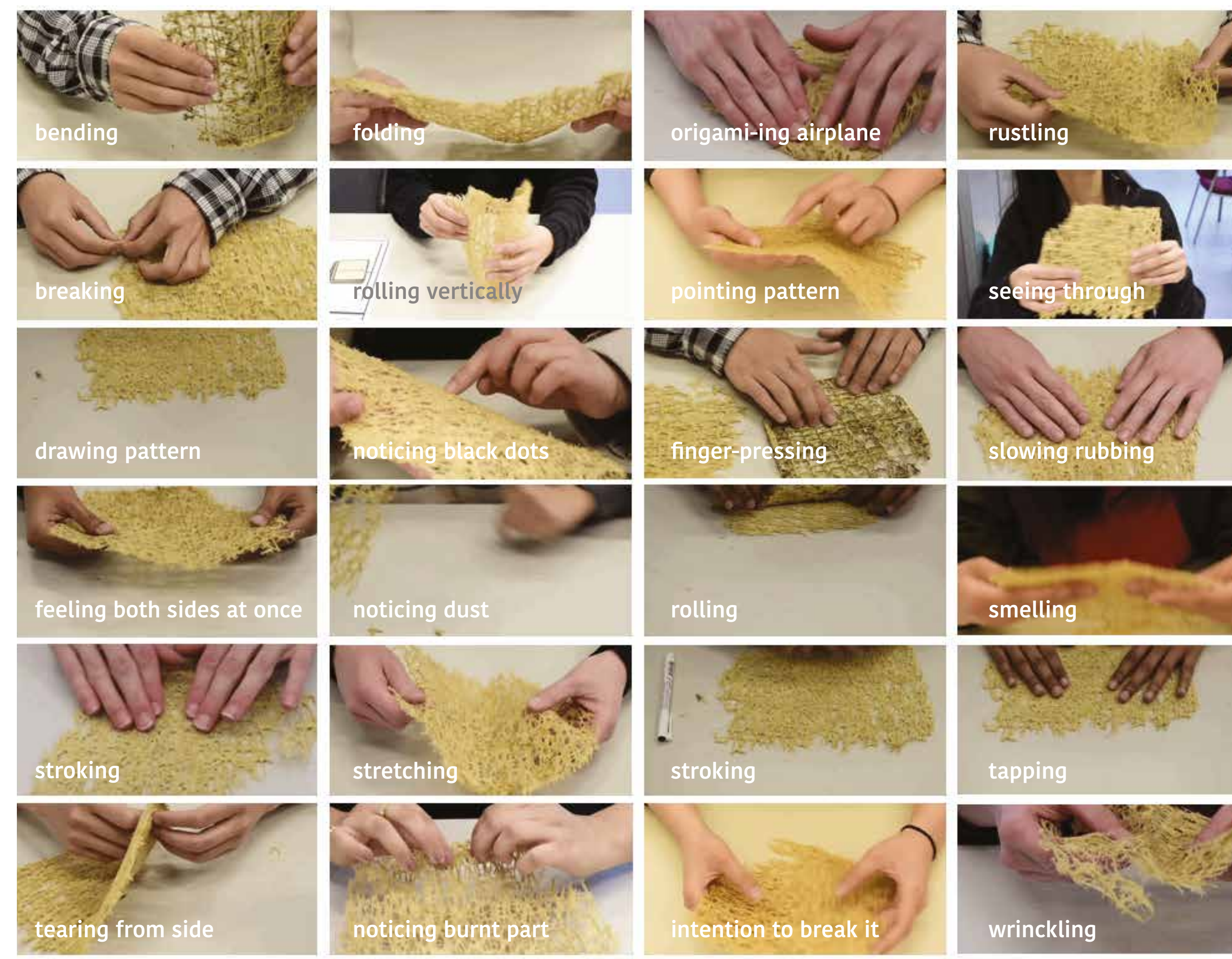

Figure [46]. performative level of Interwoven experience

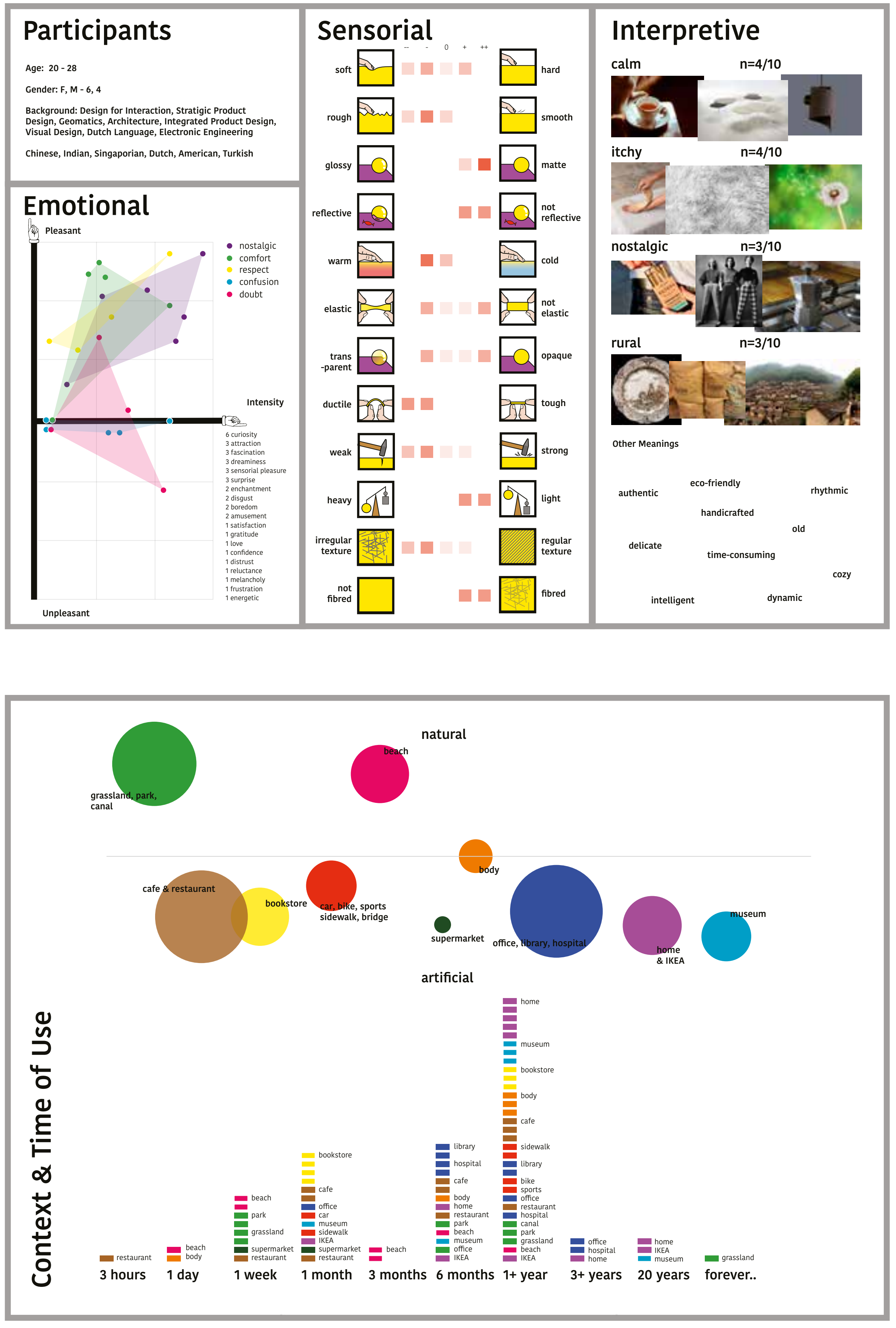

Figure [47]. Results from experiential characterisation

Sensorial Level

Sensorial properties are shown on the characterisation tool, providing an overview of the material properties. Transparency of the orange blocks indicates the number of participants who has scored the material at a certain level. In general, the material is considered to be **soft but hard, rough, matte, not reflective, slightly warm, elastic but not elastic, transparent but opaque, tough, mostly weak but slightly strong, light, irregular but slightly regular texture, fibred**.

Affective Level

Emotions mentioned 4 times and more are shown on the map, while curiosity (6 times) is not mapped and counted as an inspiring emotion due to the unfamiliarity of the material. The material triggers **nostalgia, comfort, respect, doubt and confusion** mostly. **Nostalgia** is most dominant. Confusion is slightly negative, while doubt is both positive and negative.

Interpretive Level

Out of 10 participants, **calm and itchy** are mentioned by 4, **nostalgia and rural** are mentioned by 3. There isn't one meaning that is very outstanding, instead, related meanings like calm, rural, cozy and nostalgic form a dominant meaning cluster. Other meanings like eco-friendly, authentic, delicate, handcrafted, dynamic, intelligent, time-consuming, old and rhythmic are mentioned one or two times.

Context and Time of Use

The contexts are clustered into natural and artificial, which means more outdoor/ green environment or indoor/ man-made spaces. Most chosen context of use is outdoor like **park, grassland and beach**, and indoor public spaces like **cafes, restaurants, library and hospital**. Most people think the material can be used for **6 months or more**, but **temporal use** for one week or less is also acceptable.

Final Reflections

In the final reflection, people appreciate **the pattern and naturalness** of the material, but not pleased by the **fragility and itchiness** as a textile.

The uniqueness about the material is **the organic patterns, texture and fragility in stretching and bending.** The associations are presented as images that the author found on internet based on the quotes from the participants.

"...the pattern of the summer house ceiling..."

"...cane chair from countryside homes..."

"...bird's nest..."

"...playing with sand in my childhood, or the bamboo cooling sheet on bed in summer..."

"...hay..."

"...the luffa at my uncle's place...a symbol of life and death..."

"...touching tree barks. I feel safe because it's like embracing mother nature..."

Figure [48]. Associations with the Interwoven

Discussions

Performativity
Stroking might be caused by material texture, while **the material pattern invites people to stretch and roll the material.** However, participants **don't dare to perform intensive actions**, while still intending to do something. More confident actions are seen in tapping: when people are tapping on the back side of the textile, they feel the bouncing force giving back by the sticking out spikes.

Sensorial Properties
Sensorial properties of hardness, elasticity, transparency, strength and regularity are more controversial than other groups of properties. The discrepancies in elasticity could be caused by the narrow voronoi structure, because "It seems elastic, because of the pattern, but it is not". The differences in regularity are caused by the fact that "in some part of the material, the pattern is very regular but in some part not", etc. It should be noted that, 2 participants mentioned that the material is strong in terms of resisting compression perpendicular to the material plane ("It must be comfortable to sit on"), but very weak in terms of resisting stretching force parallel to the material plane. Besides, the hollow parts in the material make some participants think it is transparent; however, other participants consider that the 'fibres' themselves are not.

Emotions Evoked
The emotions evoked are in general positive, of which nostalgia and comfort are most dominant, because of the calmness, naturalness, softness and associations with objects in the past. The confusion and doubt shown on the positive side are mainly caused by their curiosity, and on the negative side caused by material fragility.

Interpretive Meanings
Interpretations of the material vary from person to person, but meanings related to **a slowing-down life pace** are quite dominant, for instance: calm, nostalgia, and rural. It is seen as natural and handcrafted in general but **the naturalness is doubted when some participants saw that there was a geometrical structure** besides the seemingly natural voronoi pattern. One participant thinks the geometrical pattern has more human manipulation that the voronoi pattern (which appears more natural) and he was very surprised when told that the two patterns are both manipulated to the same degree.

Context and Time of Use
The material is appraised to be used more in natural recreation contexts due to its naturalness, and indoor public space for a calming effect as decorations. Although people think the material sample is very fragile, they accept it as delicate decorations like wall carpet, without much contact to human touch. Therefore, using for 1 year or more is quite common in the results.

SUMMARY OF UNDERSTANDING
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Taking technical and experiential studies of Interwoven textile, these characteristics of Interwoven are summarised:

Lack of strength: the material is very fragile in terms of resistance to tensile force and bending force (when people tried to fold the textile they found it was too brittle). However, people found it would be cozy to sit on the material and think it is stronger in resisting compressive force.

Root Hairs: root hairs are crucial in help forming a high friction complex root web, which is the natural glue in Interwoven.

Slow Life Pace: the current Interwoven textile has an outstanding emotional quality of nostalgia, which is linked to calm, rural and nostalgic on interpretive level. This is highly related to its warm color, rough touch and similar appearance to hay and luffa. However, the material is also seen as only decorative.

Confusion: some people are confused by the mix of organic and geometric patterns and think the geometric patterns are made by humans. The discussion of the naturalness and manipulation is intriguing.

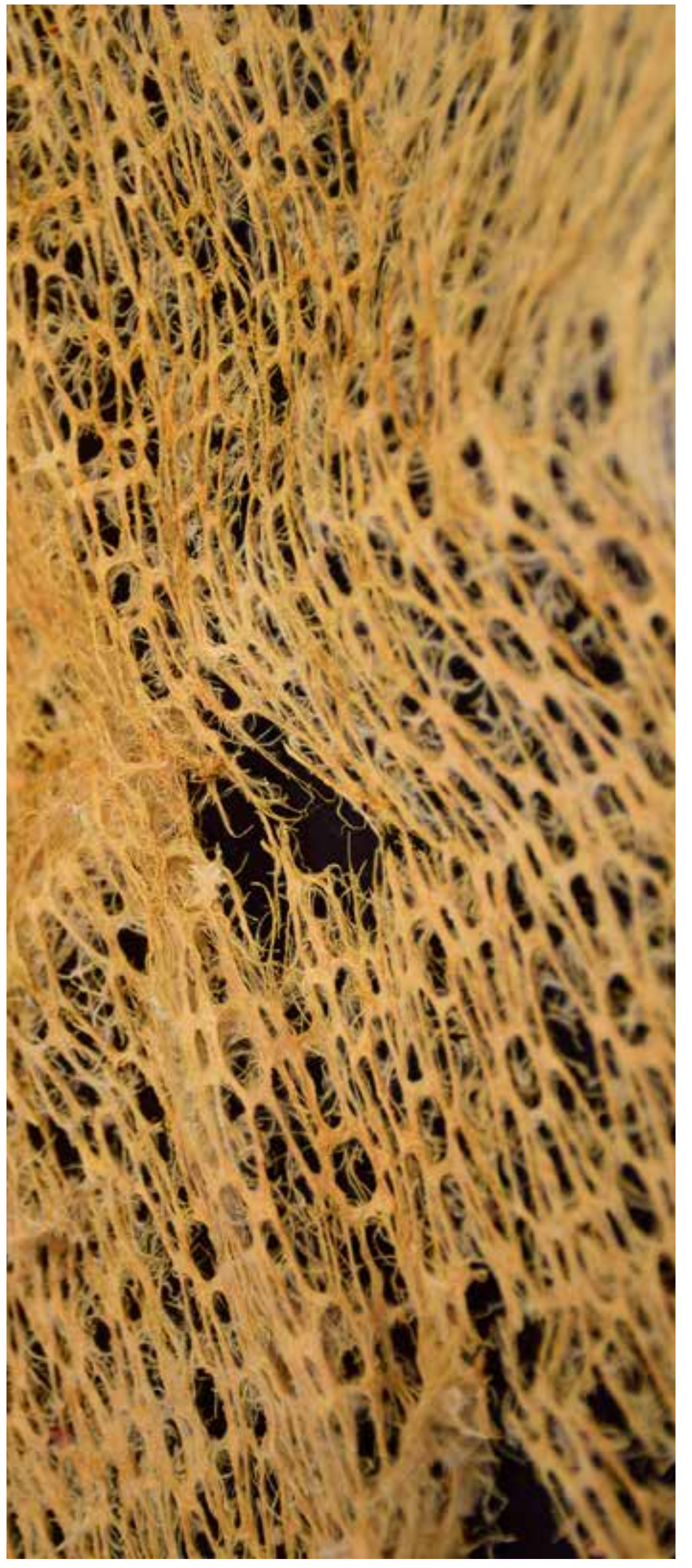

Figure [49]. A piece of Interwoven

4

Altering Root Structure

This chapter introduces material tinkering with roots. It aims to get insights on what the material affords, how it can be shaped/embodied in products, which will affect the four domains of materials experience. Playing with its ingredients, different processing techniques—helps designers to reduce the degree of uncertainty in designing with materials.

TINKERING WITH ROOT STRUCTURE

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Figure [50]. Explorative tinkering experiments

To tackle uncertainty in designing (with) a growing material, tinkering strategies could be formulated before hand. These strategies are starting points of experiments, to learn about the material while looking for insights that can be carried on. As is mentioned in the tinkering taxonomy, possible directions are dimension developing (3D & 4D), pattern developing (biomimicry pattern and engineering pattern), and compositional structure making.

Explorative to Focused Tinkering

The aliveness of the material reduced opportunities for the repeatability of certain tinkering actions and sometimes resulted in accidental findings. The designer has to adapt a sense of openness to these unexpected and/or unplanned influences of nature on the material (Karana & Camere, 2018). Therefore the first tinkering stage is explorative. The purpose is to summarise some basic knowledge about root growth principles and root behaviours in provided conditions. The illustration below shows topics covered in the explorative phase, and then 3 directions have been chosen for a more focused tinkering process. During the explorative phase, the following groups of topics are explored:

Hacking Growth
This includes **changing growing conditions and seed conditions, changing plant type**. According to the background research, understanding the biology of root growth is very important. this is to look for chances for changing material structure in the growing process, with a cultivational perspective. It is believed that through hacking the current way of growing can provide insights about root structures.

Changing Micro Structures
This is inspired by the previous microscopic examination, microstructure means how the roots are interwoven together. This might increase the strength of the material.

Changing Dimensions
Growing not just a piece of material, but a product directly is also one of the material's challenges and Diana Scherer's interest. It is also one main topic in tinkering with material structures. Learning from the microscopic examination of current textile, the roots might be manipulated to form a 3D structure.

Tinkering diary will be shown in Appendix A. Tinkering insights will be presented in next pages.

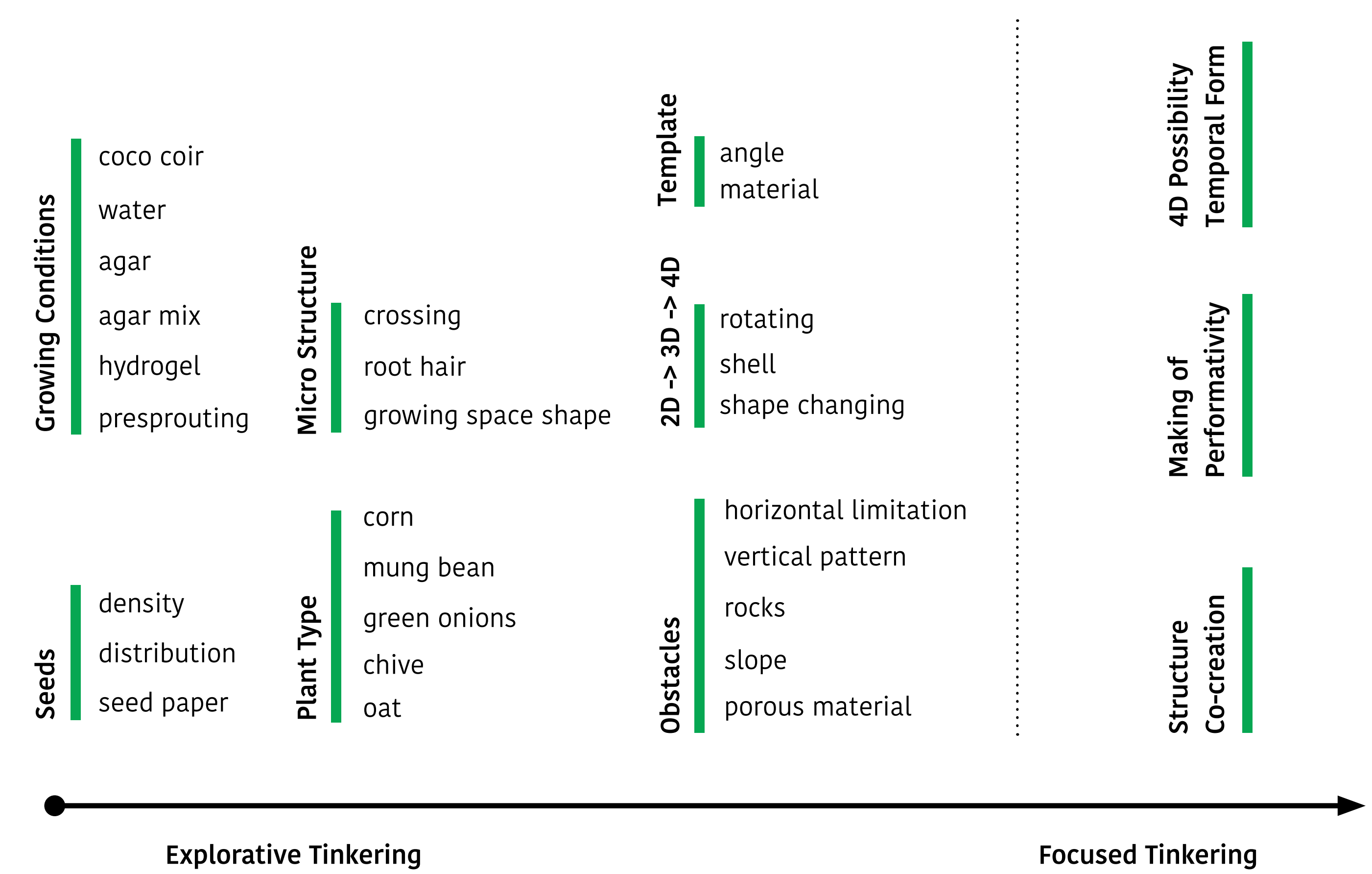


Figure [51]. Explorative and focused tinkering overview

INSIGHT I
OAT ROOTS HAVE MASSIVE ROOT HAIRS.

Plant types decide root qualities. In the experiment, five plants have been investigated, through which it was found that oat roots have most developed root hairs, essential to material strength. Green onions and chives have few root hairs by observation.

Green Onions

Root Length: short, not growing longer even when the leaves kept growing
Root Hair: zero
Root Strength:
relatively good

Chives

Root Length: long
Root Hair: few
Root Strength:
relatively good

Mung Bean

Growing Speed: fast
Root Length: long
Root Hair: few
Root Strength:
less good

Corns

Root Length: medium
Root Hair: many
Root Strength:
relatively good

Oats

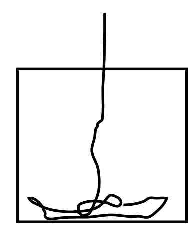
Growing Speed: fast
Root Length: long
Root Hair: many
Root Strength: less good

INSIGHT II ROOT BEHAVES DIFFERENTLY IN DIFFERENT GROWING MEDIA

Roots act similarly in coco fibres and shallow water: winding down and then spread at the bottom, while they stay more straight in deep water. In agar gel, roots absorb water and leave an agar membrane. Roots go around randomly when mixed with agar granules and extruded on a plate.

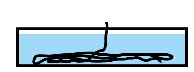
Coco Fibre

Growing Time: 7 days
Root Density: medium
Root Structure: interwoven



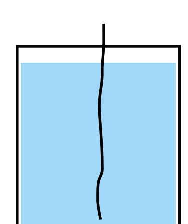
Shallow Water

Growing Time: 7 days
Root Density: high
Root Structure: interwoven



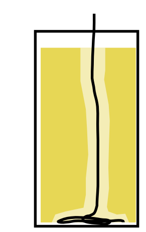
Deep Water

Growing Time: 7 days
Root Density: high
Root Structure: straight pendants in the water



Roots Eat Agar Gel

Growing Time: 7 days
Root Density: high
Root Structure: straight pendants in agar gel and woven in the bottom



Agar Membrane
Agar powder itself cannot be absorbed by roots, so after all the water has been taken, a membrane is left. Roots and this membrane link quite tightly. Roots are embeded in the membrane.

Agar Gel & Seeds Mix

Growing Time: 7 days
Root Density: medium
Root Structure: roots are going everywhere in the beginning and then interwoven together at the bottom of the container.

INSIGHT III ROOTS ARE STEERED BY OBSTACLES IN THE GROWING MEDIA.

Obstacles mean whatever roots meet in their way for water and nutrients. In these experiments, different obstables of varied material have been placed in the growing direction of roots (towards gravity) to investigate how roots react to them.

Roots only start to look for directions after they reach the limit of growing space; on a slope, roots will meander but in general still going downwards.

Learning about how roots react to obstacles to steer their morphology helps to build a repository of form languages and structural possibilities for designers. This paves a way for the next step of altering root structure, especially by changing obstacles in their growing process dynamically.

The initial aim of putting randomly distributed beads in growing media is to inspect if the beads can be taken out and get a porous 3D structure formed by roots alone. However, it proves that it is impossible to separate roots and beads because they stuck very closely together.

Hexagon Group
Growing Media: coco fibres
Hypothesis: roots will form a structure to embrace the hexagons and it will be possible to take these hexagons out
Growing Time: 7 days
Root Structure: only going down

Glass Balls & Nails

Growing Media: coco fibres (above), water (below)
Growing Time: 7 days
Root Structure: roots form a quite complex 3D web and embrace all the balls, not possible to take the balls out.

Laquered Beads with a Hole in the Middle
Growing Media: agar gel
Growing Time: 7 days
Root Structure: roots form a quite complex 3D web and embrace all the beads, some roots have gone through the holes in the beads. The complexity of the structure is very high.

INSIGHT IV MAN-MADE GRAVITROPISM CAN STEER ROOTS.

A comparison has been seen in growing in coco fibres and growing in agar gel. When the composite dries out, roots in coco fibre remains soft, while roots in agar hardens. It is also seen that roots are influenced by centrifugal force.

Growing Substrate
Coco fibres

Growing Vessel
Vase divided into 2 halves

Gravitropism
Only Gravity

Growing Time
7 days

Result
There is an obvious gradience in the clearness of the pattern in the vase. More to the bottom of the growing vessel, the pattern is clearer, while at the side of the growing direction, the pattern is hardly mirrored.

Growing Substrate
Agar Gel

Growing Vessel
A complete vase

Gravitropism
Gravity + Centrifugal Force (3n/s)

Growing Time
7 days

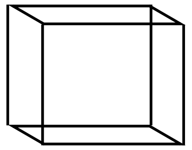
Result
The pattern in the vase has been equally mirrored at the side and near bottom. The leaves are observed to be growing towards centre, which indicate that roots are growing outwards centre.

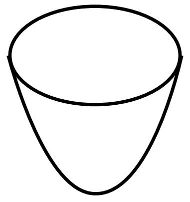
Discussion
Centrifugal force has steered the overall force to some angle from the perpendicular direction. That's probably why roots are observed to grow to sideways, instead of only downward. In this way, the patterns on the inner wall of the vase have been mirrored better.

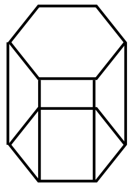
After the sample dried, the coco fibre sample is still quite soft and loose, while the agar sample becomes very hard. The shrinkage of the agar sample is also more severe than the coco fibre sample because the agar shrinks a lot. In terms of shape and pattern preservation, the agar sample needs improvement.

Growing Media

INSIGHT V
AUTONOMY SHOWN IN GROWING TRACES







The figures show roots growing trace in cuboid, cone, and hexagon pillar space. Roots show very clear growing traces and are all different. The overall form is not streamlined because roots will shrink during drying process. The overall forms are very organic looking.

INSIGHT VI
ROOTS ARE LIKE STICHTING THREADS

Materials experimentation is often pregnant with accidents, not all of them of course turn into a discovery that can be creatively explored further. Many remain a trial and error exercise. (Barati, 2019)

A serendipitous accident in the tinkering process led to an important insight: roots are acting like stitching threads in the process of looking for water and nutrients on the growing path, usually towards gravity.

Other materials and objects can be placed in the growing media (agar in this case), and roots are going to connect these descrete objects together because they tend to fill up everywhere as long as there is water and nutriention.

INSIGHT VII AGAR & ROOT COMPOSITE CHANGES WITH TIME

After drying out totally (around 12 hours after harvesting), the volume of the material shrink a lot, and the form of the unit is less recognizable. The color changes to a bit darker and burnt. It felt more rough and very stiff.

Another experiment is made to see if water can make the roots become plump again. In fact, roots do not change back. However, another insight is discovered: they absorb water and swell a little bit, and then the piece becomes very soft and comfortable to play with.

GENERAL TAKEAWAYS

Dynamic Movement
Roots show positive gratropism, but also subjective to other external force like centrifugal force. Roots react to force input of humans.

Power of Growing,
Embracing and Link to Nature
Immitating roots growing in rocks in nature, structure can be created showing the power of roots searching behaviour. They are embracing whatever is in their way towards water and nutrients

3Dimensional
Growing 3D forms is still challenging in terms of pure root material. There's possibility to combine a 3D form with the spinning model.

physical Interaction
Modular forms (patterns) give affordance to physical interactivity.

Chronomaterial
Grown in agar as substrate, the material show time-related changes. It can be seen as chronomaterial.

Clean, fresh and young
Roots grown in agar are more fresh and clean.

Leaking, penetrating
Roots ability to leak from wherever there's a hole, or to stitching whatever they can penetrate through show their powerfulness again.

Growing traces in different shapes have been concluded. In general, roots are dynamic and strong, not in the form of the final material, but in the process of their growth- in the traces of growth.

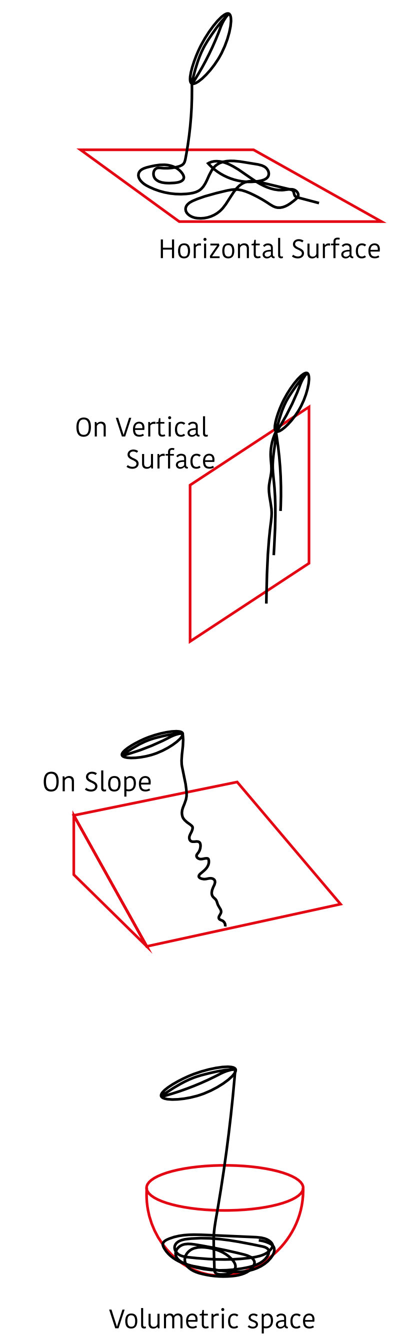


Figure [52]. Growing traces in growing shapes

ROOT STRUCTURE POTENTIAL

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As Ashby (1999) explains, it is not a material, per se, that the designer seeks; it is a specific combination of process and material attributes. (Barati, 2019) Barati (2019) has created a framework for materials potential, by revising the known potentials like form, function and experience, and adding a concept of Material Affordances. The conceptualization of affordances as material potentials shifts the focus to designers' skillful act of making and fabricating as a way of 'perceiving', 'inventing', and 'exploiting' novel affordances of conventional and emerging materials. In engineering design, the potentials might be further quantified in terms of cutting down cost and enhancing technical performances, such as 'impact resistance', relative to the existing measures (Barati, 2019).

In the experiments, some samples stood out, not because they are made of roots, but because the combination of process and root growth appears very interesting. In this section, potential samples are mapped out based on their type of potential based on the framework created by Barati.

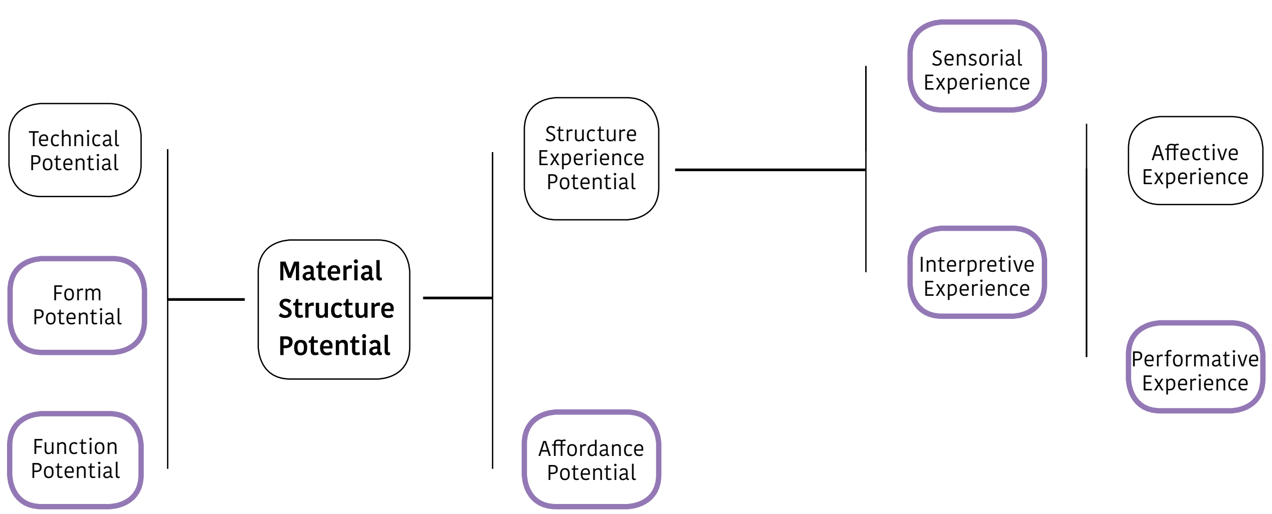

Figure [53]. Material structure potential framework

Form as Materials Potential

How the material might have enabled certain shapes. When grown in agar, roots show a shrinkage in the middle of the total root length. A waist form is created natrually. By rotating roots while they are growing, 3D form with patterns on the surface can be created. Besides, grown in agar, roots & agar composite show temporal form reactive to water. These qualities can be used in further material development.

Figure [54]. Waist form created natural during growth

Figure [55]. Rotated 3D form

Figure [56]. Temporal form

Function as Material Potential

Linking materials and their properties to the well-justified functions of existing artefacts provides an effective way to articulate the potential value and benefits of those materials. Functionally, roots and agar composite can be reshaped when moistured and hardens when dried.

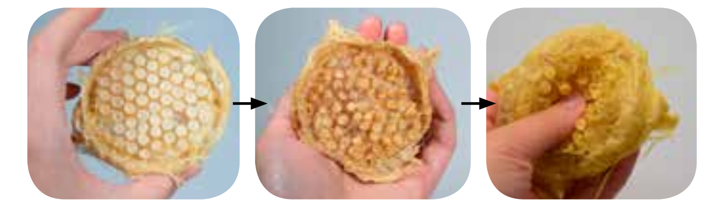

Figure [57]. Roots can be reshaped

Experience as Material Potential

Sensorial

Soft and cold, can describe roots embeded in agar membrane. Aesthetically, the material is transparent and show intricate pattern against light. It was also found that when roots lack oxygen in growing, the color changes to darker and appears burnt.

Figure [58]. Roots embeded in a soft membrane

Figure [59]. Color difference

Interpretive
Visible growing traces in different growing space show root autonomy if form giving. The traces are like design languages for designers to express aesthetics or meanings.

Figure [60]. Roots show some atonomy in their growing traces

Performative
Little extruding units on a thick piece are visual clues for people to play with the piece of materials. They could be like buttons for people to press on.

Figure [61]. Small extruding units on a round piece

Affordance as Materials Potential

Affordance as Materials Potential is what a specific material has to 'offer' in the collaborative act of people, materials, making (processes), and the surrounding environment.

This material sample shows the affordance potential of roots to offer glue-ability to other materials and surrounding environment. They could also be steered by obstacles that we create.

Figure[62]. Roots 'glue' other parts together

Figure [63]. Roots offer connection agency to other materials

EVALUATION OF POTENTIALS

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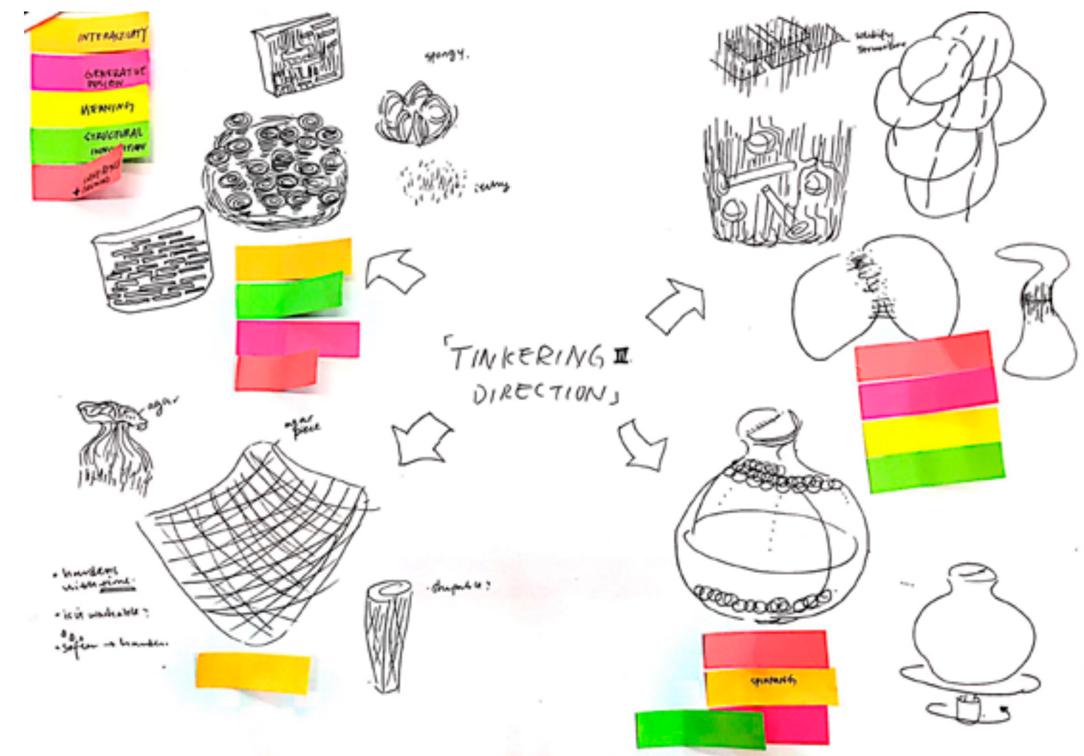


Figure [64]. Evaluation of tinkering directions

The insights and mapping of potential are analysed and convergent into four tinkering directions for a more focused and structured tinkering period. An important takeaway from explorative phase is that: **roots show their dynamic and atonomous movements, the power of growth as glue and the sensitive reaction to environment (centrifugal force, oxygen, water)**. These insights gained from the tinkering process are not experienced by people, shown by the experiential study. Therefore, these qualities will be mainly expressed in the later design of the material. After discussion with supervisors, the following directions are chosen for focused tinkering. The evaluation is based on whether this direction include structural innovation, and whether it uses digital fabrication techniques. The questions to answer by focused tinkering will be introduced in the next paragraphs.

Co-creating Structures
Roots can grow through porous structures and form a stronger whole. This means that roots can co-create a new structure with other material, as a compositional structure. What other porous structure can roots connect? What will be the difference between different structures? What other materials can be used to make the structures?

Making Performativity
Extruding units invite people to touch and play with. What other actions could be created by the units? What other shapes could invite performativity?

4D Material
Roots growing in agar gel can consume the gel and form a composite material together with agar. The composite can absorb water and become very soft, but hardens as water evaporates. What shapes can be created using this technique? What is meaningful?

FOCUSED TINKERING

#1 Structure Co-creation

More variations are made in order to investigate on how roots collaborate with existing materials and structures. Roots are grown in a growing vessel, with other materials placed in their growing path. As a result, more porous the built-in material is, the easier it is for roots to grow through and form a organic whole. Materials such as PLA and wood, also support the composite to an extended resistance to stretching or compressing.

Roots + Roots

A texitle sample made of roots has been placed in the growing vessel, and new roots are able to grow into the old ones. The result turned out to be that, the old and new roots weave together, which diminish the patterns in the old textile sample.

Roots + Textile

A Textile has been put in the growing vessel to let roots grow through. The result shows that roots have gone across the holes in the textile in a disordered way. The top part of the composite is not connected because it is where the roots need to be cut in order to harvest the material. The composite structure is not specific at the moment.

Roots + Paper

A piece of porous paper is put in the growing path of roots. The roots go very easily through the single layer of paper and form a composite. However, the single layer of paper is not able to keep the composite in a predictable shape while drying out.

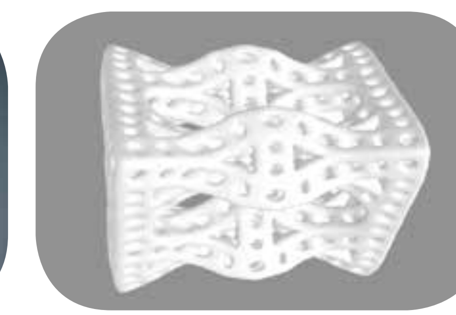
Roots + PLA Grids

Four PLA pieces are put next to each other in the growing vessel. Roots go through the pieces vertically and at the same time roots connect the four pieces horizontally. The composite takes the shape of the growing vessel.

Roots + Wood Pieces

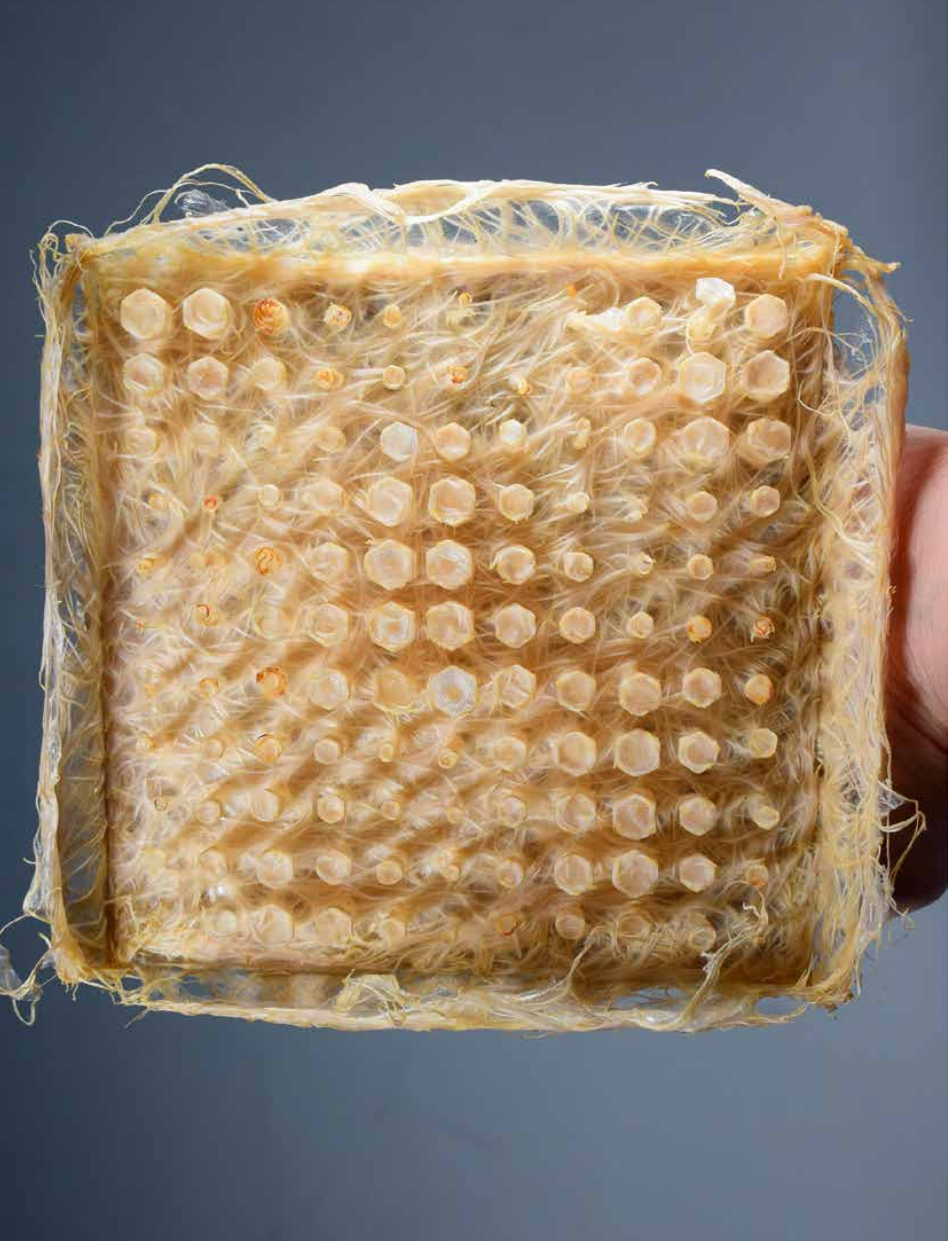
Wood sheet is laser cut into small modular pieces: triangle, hole arrays on the edges.

Roots + 3D Printed Porous



Two porous pillars have been 3D printed and placed into the growing media of roots. Roots grow into the pores and conquer the pillar all the way to the bottom and connect two pillars together. The roots act as skin to the pillar, as if skin and flesh on a bone.

Roots do not increase mechanical performace to the whole structure but a softer skin.

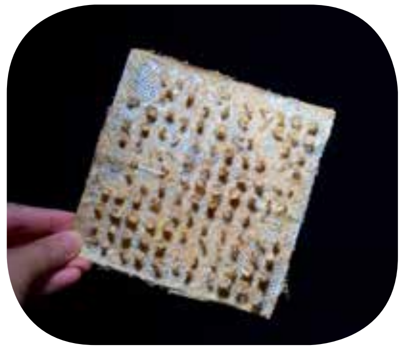


#2 Making of Performability

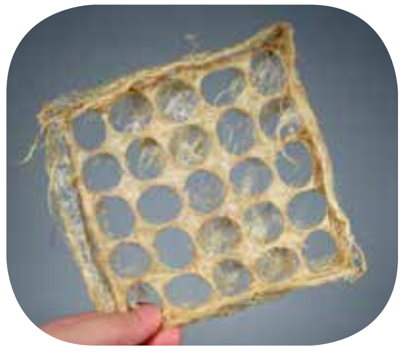
Gradience Created by Paramatric Design
Gradience has been made for the size of extruding units with parametric design technique. The purpose is to see if the resulting material show gradience in material property. As a result, the smaller unit has smaller stiffness; and the denser woven pattern shows more stiffness.


Tip Structure
A thin 3D printed piece of hexagon at the bottom of the extruding unit, roots will grow to bind the piece with themselves. The small piece prevents roots from deforming in the drying process and increase the stiffness of the tip of extruding unit.

Background Structure
4 pieces of 3D printed grids are binded by roots during growth as background strucutre. The stretchability increases. The piece looks structured and at the same time organic.




Programmable Buckling
An elastic material can have programmable buckling behaviour. Can roots have it as well? An imitation of the known structure has been made of roots. However, it doesn't show any sign of controllable buckling.

#3 4D Possibility: Temporal Form

Temporal Form
With the advancement of smart and computational materials, the temporal dimension of form has gained prominent attention, i.e., temporal form (Vallgårda et al., 2015). The temporal form in so-called computational composites is enabled by the computational structure (Vallgårda et al., 2015) and materials enable the "material manifestations of temporal forms that enable our interactions with computational things". The temporal dimension of physical form, however, does not have a casual relation to computation, meaning that materials do not always need computation to reveal the temporal dimension of their physical forms. In fact, there are many non-computational designs that invest in the natural changes of material properties and forms, over time (e.g., graceful aging, Bridgens, Lilley, Smalley, & Balasundaram, 2015) and in relation to the environment and use. Recent works on growing materials (Karana et al., 2018) and 4D structures (MIT) also take interest in material as a 'physical event' that unfolds over time. (Barati, 2019)

This experiment is to see the reshape-ability of roots & agar composite. A piece of the composite material is soaked completely and then folded into a 3D form. After several hours the piece has been sun-dried and then stays the shape. The experiment is very basic and doesn't go deeper to program the shaping of materials due to lack of time. However, some possible applications could be imagined. For instance, this could be used on a larger scale for flat-furniture transportation, where users get a flat piece but can shape it with water at home. Or in some cases the piece could be multi-functional and adaptable to use scenarios.

SAMPLES OF INTEREST

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Focused tinkering provides a deeper understanding of the grow-ability of roots and possible performativities that could take into experimental characterisation. The material strength has also been relatively increased by using agar gel as growing media and co-creating structure with existing material structure.

Tinkering is only one part of material understanding, next to experiential characterisation, technical characterisation and benchmarking. The next chapter will introduce the experiential characterisation of the chosen samples.

Finally, three groups of samples have been chosen for experiential studies. The first group consists of three flat pieces: a woven sample from explorative tinkering phase, extruding units on PLA grids, and a failed programmable buckling sample. (figure [65]) The three are chosen because they could trigger different performances due to their appearance. The second group is made up of three volumetric samples, of pure roots, co-creation with beads and co-creation with two 3D printed porous parts. (figure [66]) The third group is temporal samples with reaction to water. (figure [67])


Figure [65]. Textile vs. performativity samples


Figure [66]. Co-creation samples


Figure [67]. Temporal Samples

5

Experiential Characterisation

In this chapter, the experiential characterisation of samples of interests will be introduced. The results directly lead to the formation of experience vision as the second step of MDD method. In the end of the chapter, material concept will be presented.

EXPERIENTIAL CHARACTERISATION

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Introduction

Another experiential study has been conducted on the selected samples of interest after tinkering. The study is to answer the following questions:

- How do people play/behave with the new material structures?
- How do they rate the sensorial qualities?
- What different emotions will these structures evoke?
- How do people interpret the meanings of these structures?
- In what context do people think the materials can be used? For how long?

To answer these questions, the experiential characterization is conducted with 10 participants (different people from the previous study of Interwoven). The study will be introduced and shortly summarised in the next paragraphs.

Characterisation Tool

The same characterisation tool is used to ensure the data can be comparable to the data from experiential study on the textile sample borrowed from Diana Scherer. To be noted, although the samples are considered as a whole in the filling of the characterisation tool, through open conversations and discussions with participants, their opinions about each sample are asked and noted down in form of audio and written notes.

Participants

To ensure diverse perspectives, 10 participants from different backgrounds are invited, including 9 master students and 1 technician from Delft University of Technology. Their respective disciplines are: Design for Interaction, Architecture, Strategic Product Design, Integrated Product Design, Interior Design, Mechanical Engineering, Sound, Computer Science and Technical

Figure [65]. Textile vs. performativity samples

Figure [66]. Co-creation samples

Figure [67]. Temporal Samples

Expert. 2 of them are conscious that the material is made of plant roots but do not know about the growing process. Other participants are not aware of the fact that the samples are grown from roots.

Stimuli

Samples of interest from tinkering phase.

Figure [68]. Performative level of experiential characterisation. Left: 4D material, middle: co-creation structure, right: making performativity

Process

Each participant is invited to a one-hour session individually. The three groups of samples are presented to a participant one after each other, on the table in front of the participant. The participant is asked to play with the samples one by one and speak aloud what they think immediately. Especially, the third group of samples are required to contact water. The participant's hand movements have been observed and video-taped. Then, the participant is asked to fill in the characterisation tool, in the sequence of sensorial, affective, interpretational and context & time of use. There have been open conversations during the process, when either of the participant or the facilitator has questions. Finally, the participant is asked to reflect on the characteristics of the material, in the form of answering what is the most pleasant, unpleasant and unique qualities of the material. He/she is also asked what memory is associated with the material.

Results

The analysis of the test data is qualitative. The characterisation tool, facilitator's notes, video and audio tapes provide rich information and are all taken into consideration. (Figure [69-71])

Performative

The interactions between participants and the material samples are trimmed from the videotapes, in the form of gif animations (check the video through this link: https://vimeo.com/353433669), with annotations of what movement/actions they represent. Participants show their fascination in playing with the material structures: finger-pressing the little buttons; compressing with palm on the extrusions; putting fingers into the dented parts, etc. The co-creation structures trigger people to press. They soak the third group samples into water or pour water onto the samples and then squeeze, fold, reshape, stretch or press the extrusions.

Sensorial

Sensorial qualities are shown on the characterisation tool itself, providing an overview of the material properties. Transparency of the blocks means the number of participants who has scored the material at a certain level. The blue dots represent the material properties after watering. In general, the material is considered to be harder, tougher and stronger, compared to the textile sample in the first experiential characterisation. Water makes the material change its properties: softer, smoother, colder, more elastic and more ductile.

Affective

Emotions mentioned 4 times or more are shown on the map, while curiosity is not counted as an emotion that inspires the design because it can always be evoked when people see something unfamiliar and new. The material triggers rich positive emotions, such as nostalgia, comfort, surprise, amusement, fascination, dreaminess and sensorial pleasure, of which nostalgia and comfort are still most dominant. Negative emotion is mainly focused on doubts .

Interpretations

Associations with the material have a few changes: firstly, the dominant association shifts from calm to eco-friendly and more meanings take evenly distributed dominance; second, itchiness becomes less obvious; new meanings arise, such as wild, surprise, mysterious, sensitive, funny, fresh, exotic, while some previous meanings disappear, such as handcrafted, old and cozy. Regarding the context & time of use, there is a clear shift from natural environment and public indoor space to supermarket and home. Associations of different samples are concluded in figure [68]. New meanings are mainly associated with sample of extruded units and co-creation samples.

Reflections

In the final reflection, people appreciate the versatility and possibilities the different sample present, and the surprise it brings in the aspect of "not that fragile", "soft feeling after soaking", the naturalness and peacefulness and the intricate patterns; they don't like the unstructural visual effect and the doubt about its reliability. The uniqueness of the material lies mainly in both organic and structural form which blends nature with artificial world and the dynamics and crazy growth.

Discussion

Performative

People are fascinated in playing with the material, especially triggered by the form or structure of the material. The little extrusions invite people to press them, and the round shape invite people to pick it up from the desk. This means that by changing the form or surface structure, a certain behaviour will be triggered. This is also shown in the watering samples: hard samples invite people to bend and press, while soft samples invite people to stretch, fold and even put on

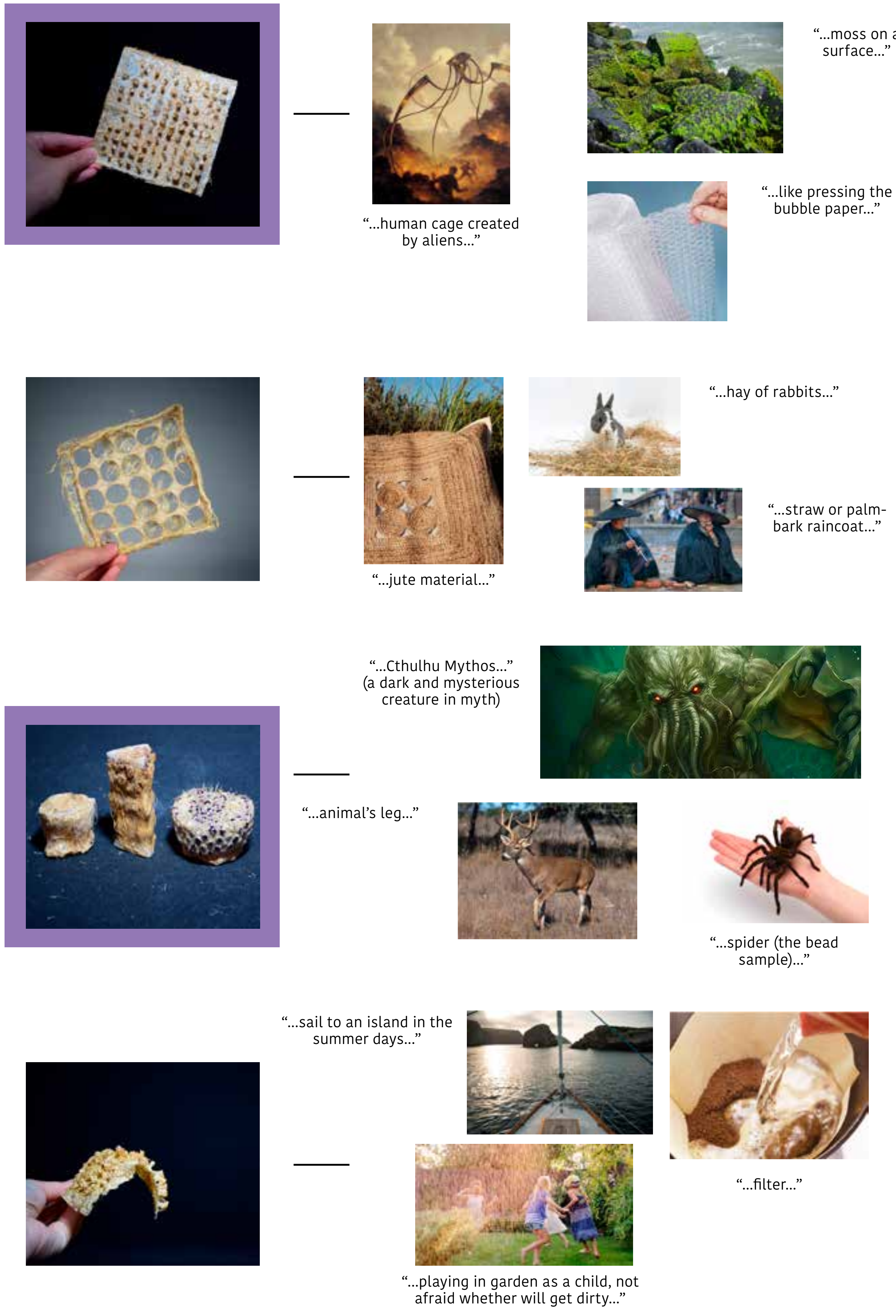

Figure [69]. Associations triggered by tested samples

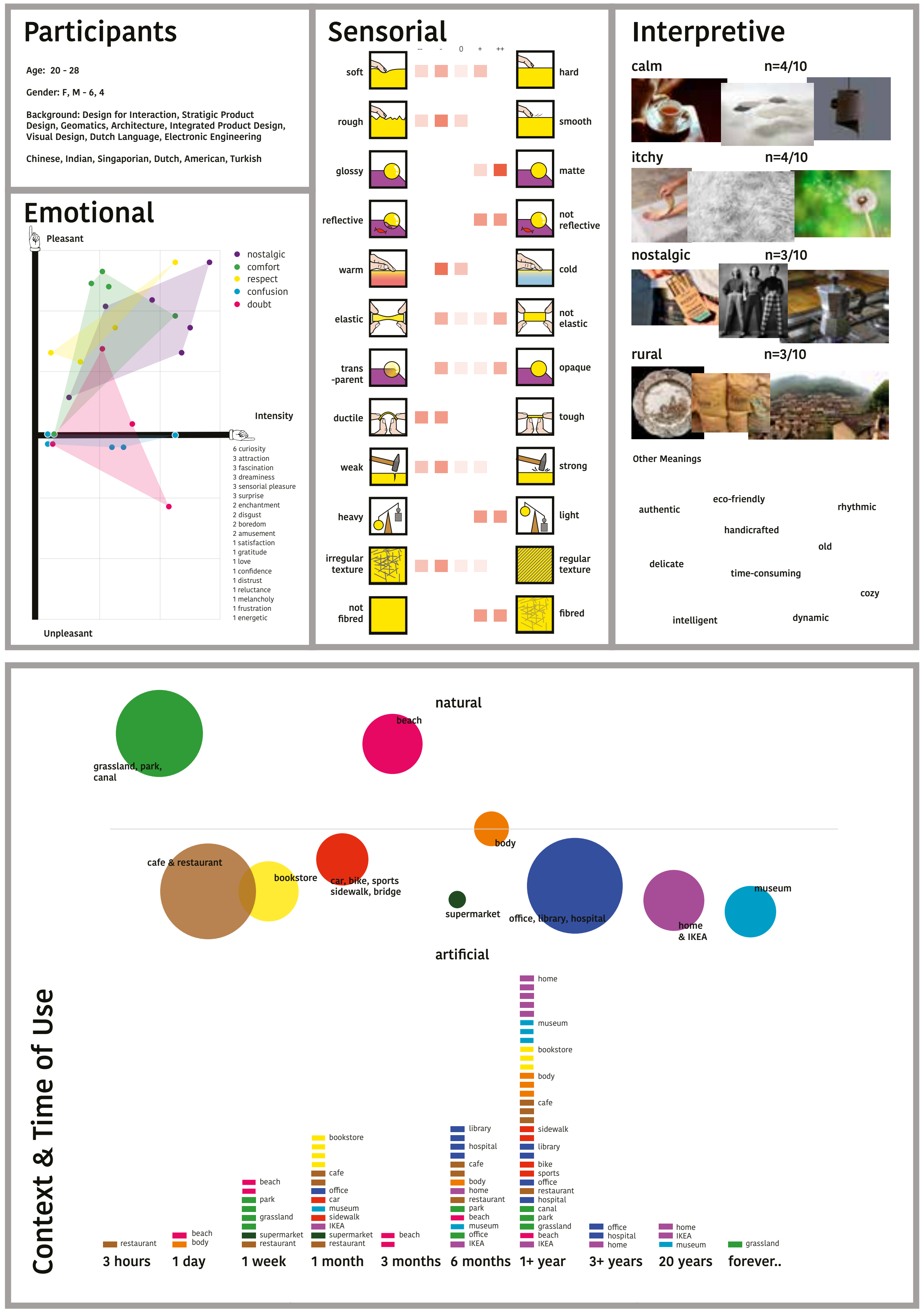

Figure [70]. Experiential characterisation results for Interwoven textile

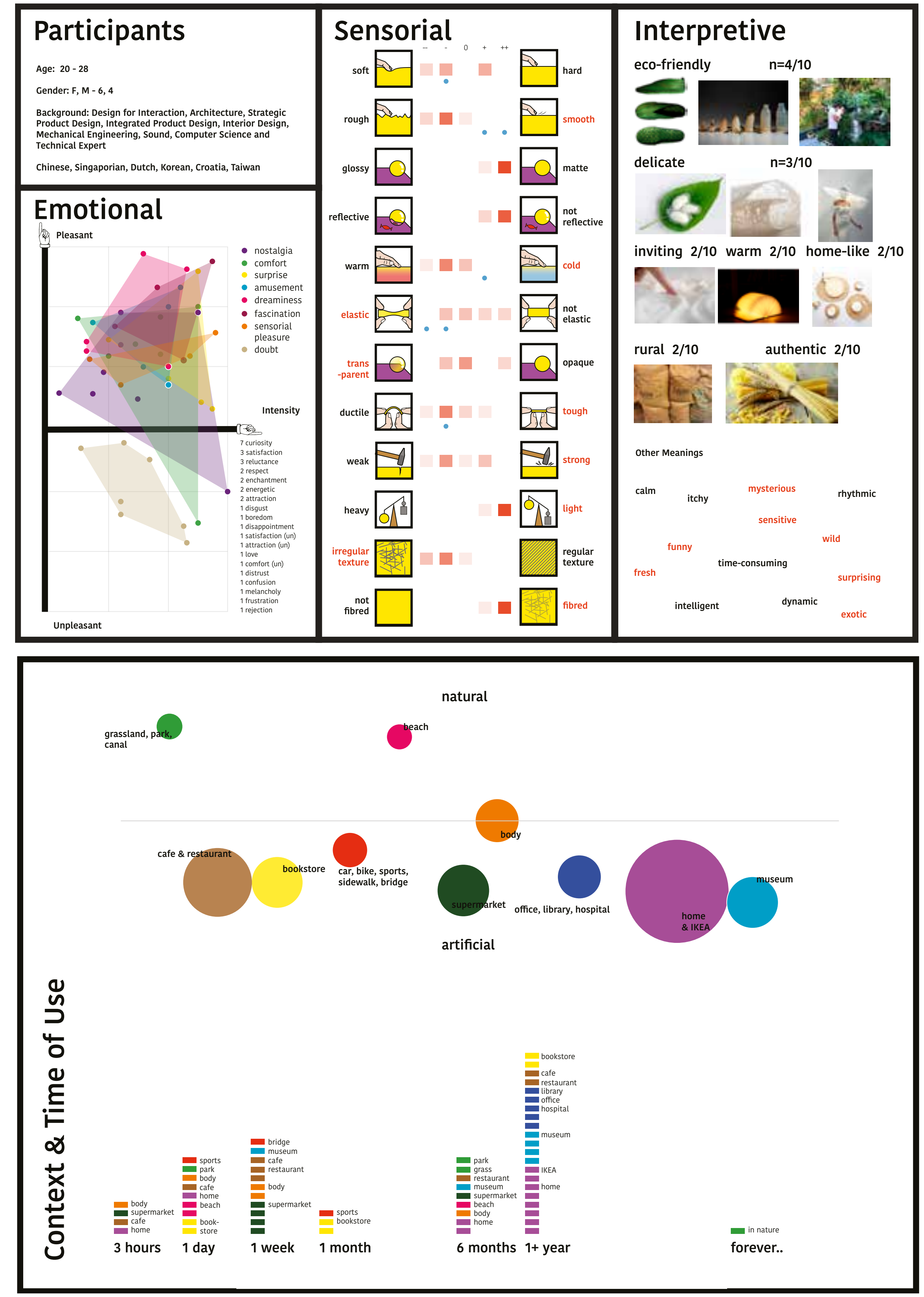

Figure [71]. Experiential characterisation results for developed samples their skin. In general, the interactions are very tentative and careful in all samples because of the fragile look. However, this also explains the surprise at the actual strength of the co-creation samples.

Sensorial

The material is still appraised as quite fragile, but in the open conversations, people indicate that "it is fragile, but not as I thought", "the bottoms provide some push-back, which I didn't expect". This quality can be concluded as sensory incongruity (Ludden, 2018), which gives people surprises during use. The surprise is also reflected by the fact that when people are told that the "animal's leg" sample is made of two separate pieces connected by roots, they are impressed by how tight the connection is.

Emotional

The richness of emotions might be because people are exposed to more samples with diverse features, but admittedly, these samples evoke more surprise, amusement, dreaminess and fascination; at the same time, the doubts are more obvious and negative than the previous textile sample. This might be because the new samples look more unfinished and unorganised, which make people doubt due to irregular forms of some samples, fragility and potential to contain dangerous microorganisms. To reduce the doubt, more organised and precise structure is needed.

Interpretive

The shift from calm, itchy, nostalgia and rural to eco-friendly and delicate as the most dominant meanings can be explained by the fact that people see the material as more man-made than naturally made. This is also reflected in the rising associations like "human cage created by aliens", which put the material more to an alien and futuristic background.

Context & Time of Use

There is a huge shrink in the imagination of using the material in a natural environment and indoor public space, while expansion in using in the supermarket and home. Considering that home and supermarket mean more ownership and durability than public areas, it could be concluded that the new samples are considered as applicable in their daily life. This is a good result, considering bringing the material closer to people's life, which belongs to one of the visions of Diana Scherer.

Reflective Questions

Instead of pure rural and nostalgic images, these samples provoke people's thoughts on a philosophical level. They are not only a physical material, but also have the potential of raising critical questions: how do nature and human manipulation work together for an applicable material? What is the boundary between natural growth and man-made objects? Although people are not told in advance that the material is grown from seeds, they are aware of the "crazy growth". Compared to the previous textile sample, which was seen very linked to nature, there arises a sense of powerful growth, with a hybrid alien feeling.

The 4 levels of experiential qualities are closely linked to each other. Irregular texture triggers people to touch them, so people think the material as inviting; but at the same time the rhythmic arrangement of organic forms create a mixed feeling of "wild" and "intelligent". From this touch, people feel comfort and sensorial pleasure, which keep them playing continuously. The material is considered to be warm and calm, because of the naturally warm yellow-brown tint, association of nostalgic objects and environment and fascination in playing with it. Meanwhile the material is considered delicate, which can be associated with its intricate patterns. However, this is also highly relevant to doubts about the reliability. Eco-friendly is independent from other features but is one of the most important features of the material, which help people build trust. Last but not the least, the surprises most participants feel are caused by some sensory incongruity, for instance: seemingly fragile but not that fragile, very alien and organic but structured structure etc.

Conclusions

As a conclusion of the experiential characterisation, these two material qualities can be concluded as most unique qualities:

The Power of Growth

The power of growth is on one hand perceived in the co-creation structures, where roots bind small beads together. Power is also reflected in the increased strength people perceived. The material alone is still fragile and make people doubt. However, when a compositional structure, people feel surprised at how strong it is. Additionally, roots alone can only resist tensile force, but with compositional structures, the whole body can resist compressive force.

On the other hand, growing traces in extruding units express a sense of "crazy growth".

A Blend of Nature and Artificial World

A blend of nature and artificial world is reflected by two facts: first of all, the structure is co-created by natural roots and the connected man-made material/structures; secondly, the blend is expressed by the natural traces of root growing in the extrusions in a designed and organised arrangement.

Above all the features, the materials with co-creation structure provokes participant rethinking about nature and man-made world. Particularly, one participant got very confused at one sample since it looked really like 3D print, but like a living organism as well. The dramatic and mixed meaning the material triggered in people is riding on the trend of bio-digital fabrication nowadays.

MATERIAL CONCEPT

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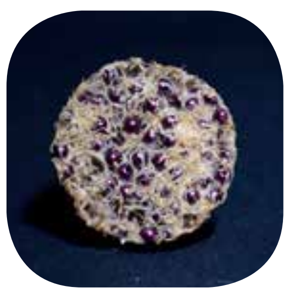
Introduction
This material concept is developed from Interwoven by Diana Scherer. It is made up of two structures: the body and the skin. In this concept, roots weave into other material structure vertically.

Body
The material concept consists of a "body" and a "skin". The body means supporting part which provide strength to ensure functionality and durability. The sample chosen is the co-creation sample with small beads. The experience is mainly led by interpretive level: intelligent, wild, rhythmic, mysterious, alien and surprising.

Skin (optional)
The skin is the sample with gradient extruded units, which indicates root autonomy and show their growing traces to present a sense of growth. The experience is led by performative level, that people want to press on the buttons, and also an interpretive level of the conflict of structured but organic form. It invites people to touch and inspect.



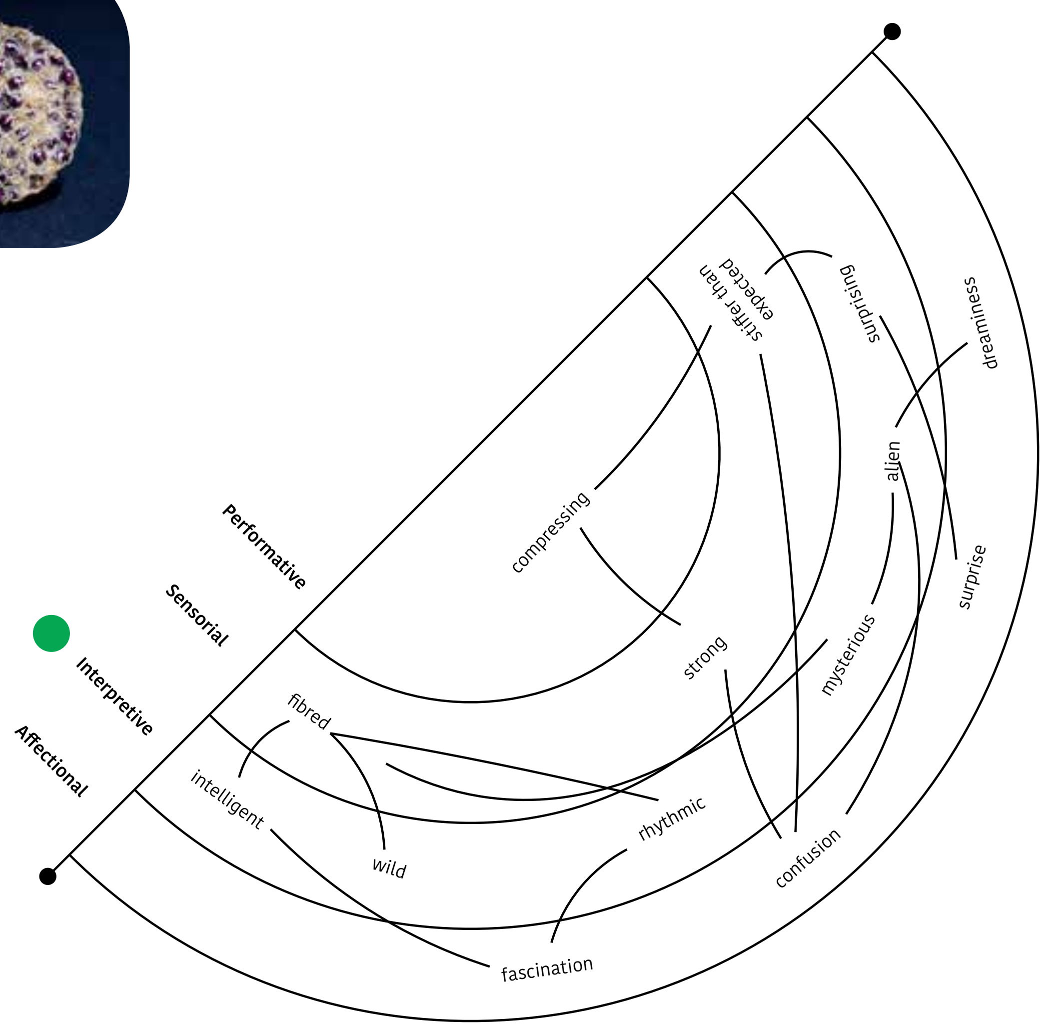
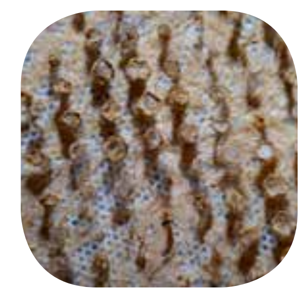


Figure [72]. Relationship between four levels of material experience



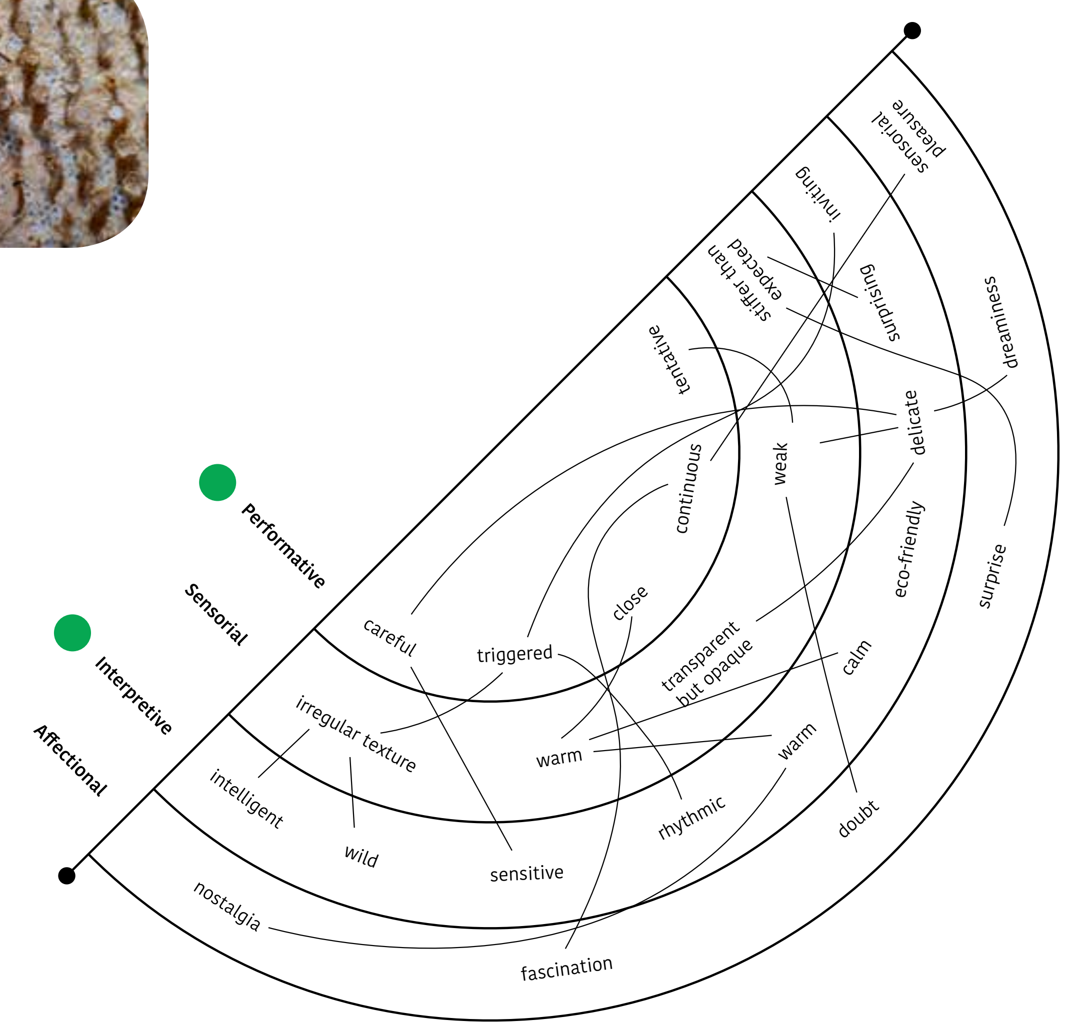


Figure [73]. Relationship between four levels of material experience

6

Experience Vision

This chapter introduces the experience vision formulated based on the material concept, material benchmarking and trend summary. Material unique qualities are analysed, material benchmarking is introduced and material trend is summarised. These all lead to the experience vision.

QUALITIES OF MATERIAL CONCEPT

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Experiential Qualities

This concept emphasizes the power of growth and hybrid feeling caused by root structures: the natural structure formed by roots in their way of searching for nutrients and space. The co-creation presents interactions between organic and man-made materials and bring this conflict and collaboration forward, while organic but structured extrusions invite people to touch and observe the trace of growth.

Based on the material concept, the experiential characterisation can be classified in six segments, referring to the four experiential layers of a material: sensorial, interpretive, affective and performative.

- The unique qualities: weak but strong; sense of growth; structured but organic patterns; a blend of nature and man-made
- The most and least pleasing sensorial qualities: out of control; don't know the reliability; fascination in patterns
- Associations: mysterious creature, bubble wrap, human cage created by aliens, spider, moss on a surface
- The meanings the material evokes (interpretive layer): delicate; inviting; rhythmic; wild; mysterious; dynamic; intelligent; surprising; funny; exotic
- The emotions the material elicits (affective layer): comfort; sensory pleasure; doubt; surprise; dreaminess; fascination; amusement
- How people interact and behave with the material (performative): bending, pressing

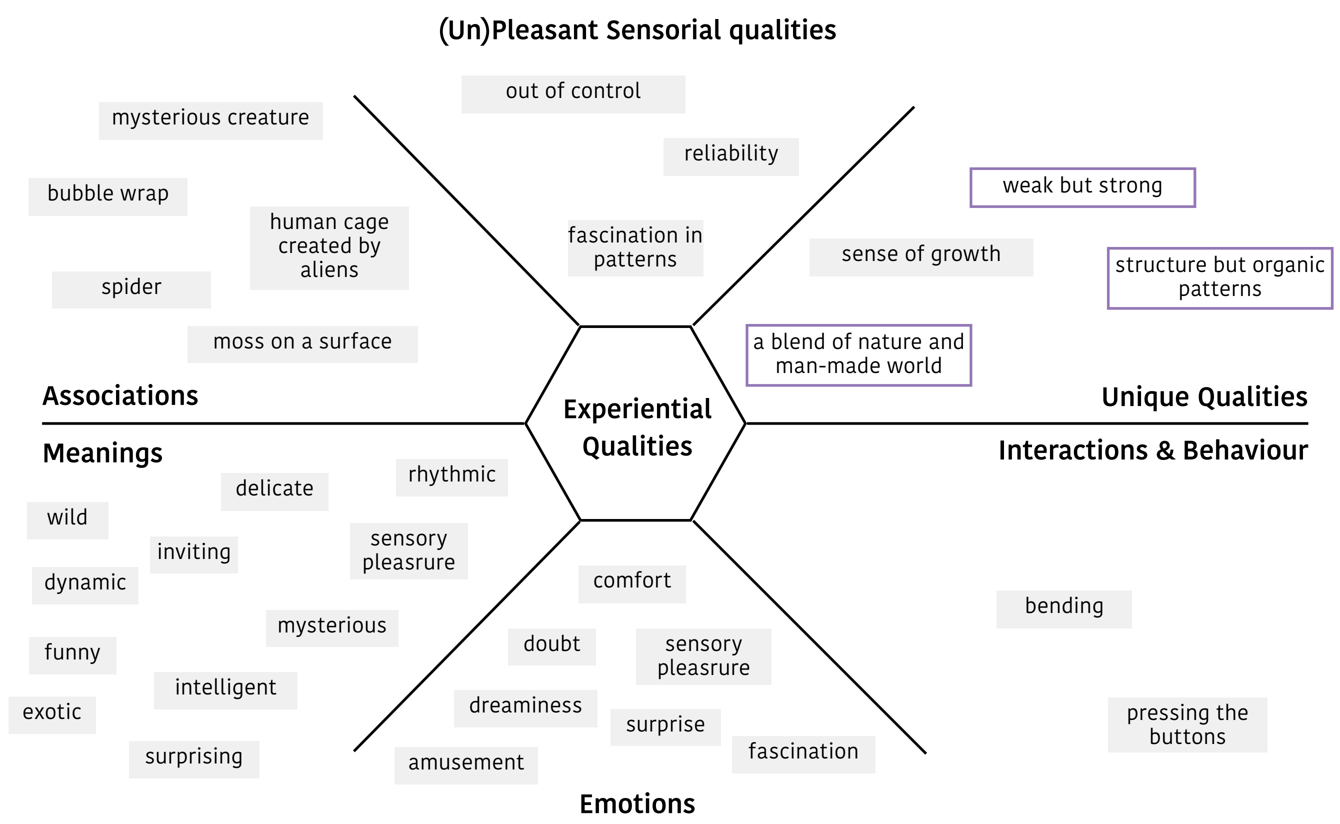


Figure [74]. Experiential qualities of material concept

Technical Qualities

The co-creation structure is an opportunity to make roots as a daily material in people's life since it makes a stronger whole than roots alone. It also transfers such a delicate material structure into a robust volume. Roots are not only compostable, but can also be durable.

The figure shows the technical characterization of the material concept, which is divided into five segments that refer to:

- The key technical properties; (rough, stiff, growing, glue-ability; compostable)
- The most convenient manufacturing processes; (growing through existing porous structure; growing in agar gel; growing in template; generative modelling)
- How the material behaves when subjected to other manufacturing processes; (getting dirty and only 2D, getting fragile, not structured,)
- The technical constraints; (fireproof; water deformation; growing length; production time; species dependant)
- The technical opportunities; (co-creation; variations in structure; growing; compostable)

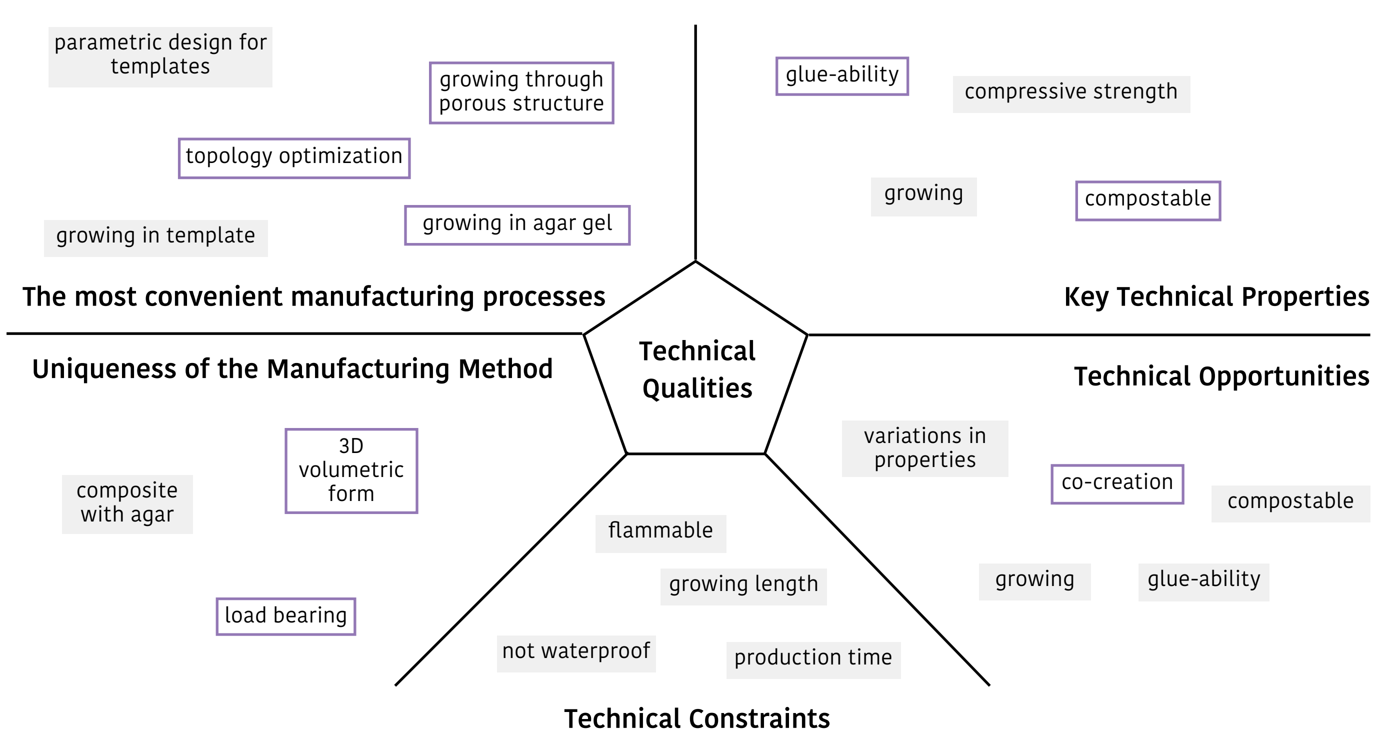


Figure [75]. Technical qualities of material concept

BENCHMARKING

Introduction

Material benchmarking is used to position the material concept amongst similar and/or alternative materials, to generate insights on potential application areas. It will also reveal emerging materials experiences and other emerging strategies, or values increasingly emphasized in the last decades (Karana, 2015). In this section, two benchmarkings are made: 1). The phenomenon to manipulate nature to fulfill human wishes; 2). The purpose to enhance natural materials.

Manipulating Nature

This benchmark shows examples in which human beings put certain interventions to the natural state of growing conditions of living organisms, in order to do a certain research or reach a human goal. This area has certain overlaps with growing design and digital biofabrication (Camere and Karana, 2018) but it emphasizes on the man-made interventions to take advantage of the natural process to produce something for human beings. The manipulation techniques include: reforming growing space/direction, guiding living organism with food, changing gravity, creating a man-made habitat for living organism. The current practices to manipulate nature are analysed in terms of material characterisation, making process and human activities. The full benchmark data sheet will be found in Appendix B.

Guiding with Food
Experiment

Mycelium Structure, 2015
Gianluca Tabellini
Bacteria printed on paper

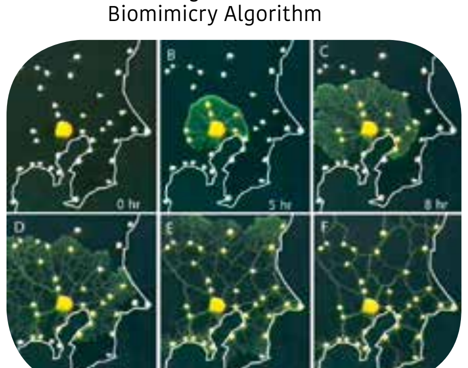
Creating a Man-made Habitat
Sculpture

The Honey Comb Vase,
2010
Studio Liberty

Guiding with Food
Visual Product

Symbiosis, 2009
Jelte van Abbema
Bacteria Printed on Paper

Guiding with Food
Biomimicry Algorithm



Research in Network
Formation in Physarum
Polycephalum, 2010

Reforming Growing Direction
Bridge

Living Root Bridges, Long
History
Bangladesh

Reforming Growing Direction
Daily Furniture

Full Grown Chair, 2012
Gavin Munro

Figure [76]. Manipulating Nature

Enhancing Natural Materials

This benchmark shows current practices to enhance natural material strength including adding resin, designing material structre, and creating composite structure. The figures below shows the main three types of enhancing. For more details of other practices and information please see Appendix B.

Adding Resin

Artichair, Kizi Studio, 2015

Material Structure

Bamboo Furniture System, sandeep
sangaru, 2010

Composite Structure

Mycelium Chair, 2013,
Eric Klarenbeek

Figure [77]. Enhancing Natural Materials

Opportunities for Interwovens

Taking all the benchmarks into consideration, Interwovens has potential to not just acting as a surrogate to others (Rognoli et al., 2015) but also to be identified by its own unique characteristics that and be expressed and embedded in an appropriate design (Camere & Karana, 2017). The opportunities for the material lie in these aspects:

- **Fast Produced Daily Product**: Full Grown creates daily furniture but it takes so long to produce one. Few examples in the first benchmarking could be daily products produced fast that people get easy access to. Plant roots are fast growing materials and thus have the potential for designing sustainable daily products.
- **Versatile Material Qualities**: existing materials usually show limited properties, for example, a material is stiff and hard in all parts; however, it is possible to change properties of Interwoven by altering the inner structures and changing the shape of growing space. This enlarges the potential of Interwovens to fit different purposes.
- **Enhancement Happening in Growing Process**: many of the enhancement happens after production of the material. However, the research and development of this study demonstrates that enhancement can happen during the growing process. Agar gel can add an enhancing membrane to the material, which is unobtrusive and ubiquitous inside the material structure, forming a holistic structure. In the current material practices, adding resin is still popular to enhance a natural material, which can do harm to the environment and kills the sustainable nature and delicate look of the natural materials.

INTERWOVEN & VISION

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Figure [78]. up: co-creation with beads, down: extruding units

Experience Vision

To exhibit the glue-ability of Interwoven through a daily object co-created by roots and digital manufactured structures and bring forward the collision and collaboration between natural growth and man-made world.

Material Trend Summary

Material trend summary is based on the benchmarking. It summarizes increasing strategies and values in design domain in recent decades. They will be considered for material experience vision.

Uncovering Natural Resources:
In growing design practices, plants and microorganisms provide abundant raw materials for material development. For instance, abundant pine needles in a certain area, or wasted fruits from daily consumption have been used to develop durable biodegradable materials. Material developers are exploring untapped parts of nature that have potential to sustainability. Plant roots, have not been considered as a product material yet and remains open for further exploration. The closest to growing roots is the growth of mycelium materials.

Collaboration between Digital and Biological Fabrication:
Digital fabrication brings to growing design new dimension and possibilities. It helps locate the growing matter and instruct the form of the final outcome. The Silk Pavilion project from MIT Media Lab explores the collaboration between digital fabrication and biological fabrication on a product and architectural scale. (https://www.media.mit.edu/projects/silk-pavilion/overview/). The primary structure was made from 26 polygonal panels made of silk threads laid down by a CNC (Computer-Numerically Controlled) machine. A swarm of 6,500 silkworms was positioned at the bottom rim of the scaffold spinning flat non-woven silk patches as they locally reinforced the gaps across CNC-deposited silk fibers. This collaboration is similar to Interwoven, where the template is designed digitally while the growth is activated by the organism itself.

Shift from Criticism to Acceptance:
Communities from the sciences and social sciences are looking to critical design practice and see potential for its application in an ambivalent zone between emerging science and material culture (Malpass, 2017). Material developers are questioning the role of nature in design, such as rethinking the production of artefacts to be more renewable and sustainable. Some products are considered to be critical design (Malpass, 2017) and not fully functional. However, more and more material developers are making an effort to work out a functional material innovation, instead of speculative one. They are also trying to fit these materials into new models of business, such as Cradle 2 Cradle (Mcdonough et al., 2010).

Experience Vision

The material experience vision is based on material concept, material qualities, material benchmarking and material trend summary.

Through the studies in the research in this project, it is known that roots grow towards gravity to find nutrients and water, and in this way, they can connect porous structures and glue them together to be a hybrid material. This co-creation has turned a weak flat piece into a three-dimensional and more robust one, which could benefit both materials and human use. By making a skin with extruding units that showing the growing traces of roots, the material makes people fascinated in looking and touching.

Experiential studies show that a conflict and collaboration between natural growth of roots and human manipulation is presented through the material concept. Benchmarking and trend studies show that the concept should be designed to be a daily object that people can get access to easily, but at the same time raise curiosity and provoke reflections about mass manufactured products in their daily life. Besides, for future research, the potential to further design inner porous structures in the body of the material concept, will enable the material to be more versatile, meeting different functions in product design.

Thus, a material experience vision is created:

Interwoven: to exhibit the glue-ability of Interwoven through a daily object co-created by roots and digital manufactured structures and bring forward the collision and collaboration between natural growth and man-made world.

7

Product Concept

This chapter introduces how the material experience vision pattern is studied and product conceptualisation process. The detailed design and iteration process will be introduced.

IDEATION

-

Introduction

In order to find out a concept that reflects the design vision, a brainstorming session has been conducted amongst 3 students from Design background, including 2 master students from Integrated Product Design, and the author (from Design for Interaction). Since the vision aims to design something that is functional and durable but at the same time provocative, the ideation is aimed to find object/space or phenomenon based on "strength" and "a blend of nature and artificial world".

Figure [79]. Ideation session

Process

The process consists of two phases: the first round is ideation without introducing the material samples; the second round is after introducing the material samples. In total, two rounds of brainstorming are conducted. Each round is a brainstorming of applications based on the two keywords.

Firstly, the design students are introduced to the design vision and explained about the key elements. In this around, the ideas can be unrelated to the material. Not showing the material samples in advance help broaden possibilities, without pre-judgement of material capabilities. For each keyword, the students are asked to draw product/space ideas on an A3 paper respectively within 10 minutes. After that, each student introduces their ideas. In the meanwhile the students can discuss about the ideas, what they like about the ideas and generate new ones inspired by them. The same process repeats for the second keyword.

The second round begins with showing the students material samples. These samples act like design languages or brush types for painting, because they indicate possibilities of forms and structures. And then the students played with the samples and asked a few questions, in order to know the features of each sample. The samples are put aside on the same table during the ideation, so that the students could have access to them. The same process went for the second round. After all, the students are asked about their overall opinions about how to show the vision with the material.

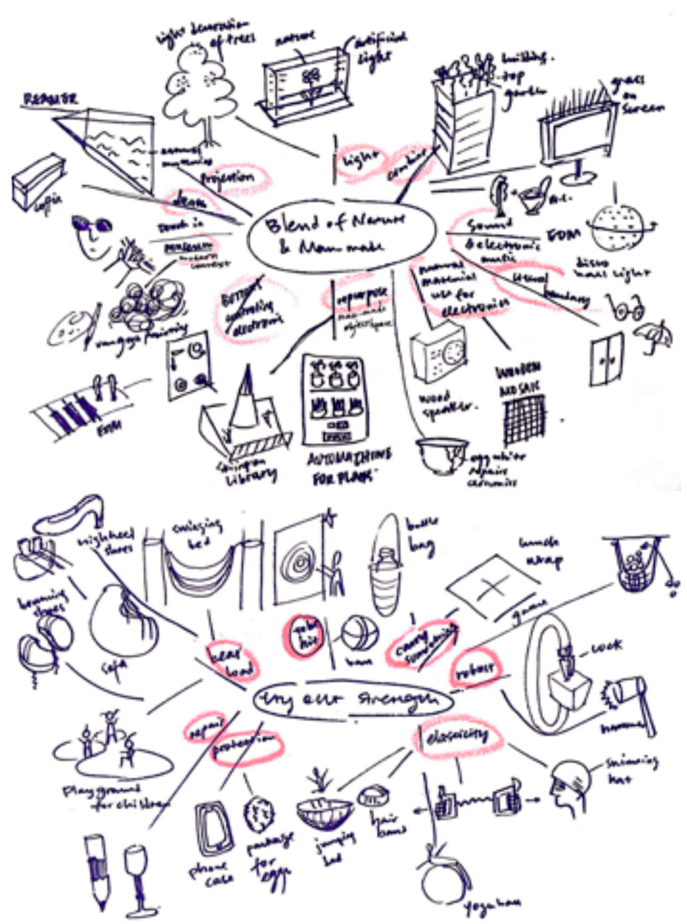

Figure [80]. Ideation summary

Results

The ideation sketches will be shown in Appendix D. Based on the keyword "Strength", more than 20 ideas have been generated. They are then sorted out and divided into 7 themes based on performativity:

- **bearing load**
- **to be hit**
- **hitting other objects**
- **repairing other objects**
- **protecting other objects**
- **showing high elasticity**

Coming from "Blend of Nature and Artificial World", some phenomenon and strategies are concluded:

- **using artificial light for raising plants;**
- **building plantation/landscape on modern architecture or computer;**
- **having natural materials in disco scenarios;**
- **using natural materials for sunglasses, sun umbrella or windows;**
- **using natural materials to design electronics;**
- **using natural materials to show digital aesthetics like mosaic;**
- **using egg white to repair ceramic bowls;**
- **repurposing man-made object/space for natural recreation;**
- **buttons made of natural materials to control EDM;**
- **creating a touch of nature in museums;**
- **projecting digital media on natural screen.**

Experience Vision Patterns

Based on the ideas and their iterations, some design principles are discussed by the students and concluded as follows:

- If the object/space is placed in a public space, it should attract the attention and arouse curiosity for people walking around to try out (the strength); if it is owned by someone, strength should be shown by its durability.
- The ability to repair or connect porous parts is a unique feature of root growth. To utilise this feature, discarded porous materials that need connection can be considered. For instance, discarded foam, crushed plastics, discarded cotton, wood and paper. Besides, 3D printing technique can also produce porous structures to purpose. For example, a skeleton or bone structure.
- If the design is at body scale, ideas are more focused on compressive strength; if it is at hand scale, ideas are more focused on tensile strength and elasticity.
- A blend of natural growth and digital fabrication can be shown by gradient transition of roots and other materials, or showing the growing pattern through external techniques such as lighting and shadow. Meanwhile, the context of use can also trigger thoughts about the collision between nature and man-made world. Such as, electronic devices made by roots or the co-created structure.
- The design should invite people to touch and push/press/stretch by using visual cues such as intricate patterns that make people want to look carefully. The more precise the pattern is, the more fascinated will people become.
- Light is a good way to show the growing traces.
- If the design can keep the grasses still alive, or take the growing process into consideration, it will be more interesting.
- A transition of pattern of material properties show the potential of the material and make people more curious about it.
- Designing something familiar but using delicate looking materials will make people curious and want to try out material strength.

CONCEPT DEVELOPMENT

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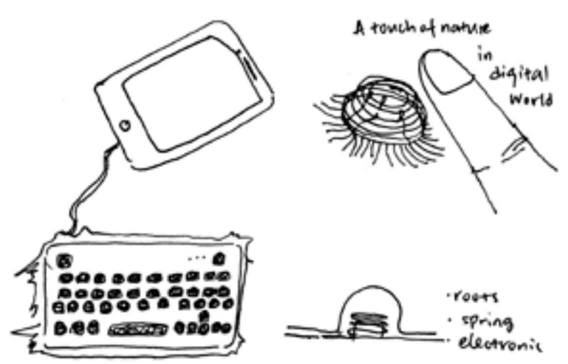
Based on the principles discussed from ideation, five concepts have been conceived. Each concept will be presented and discussed in relation to the vision and the gap it addresses.

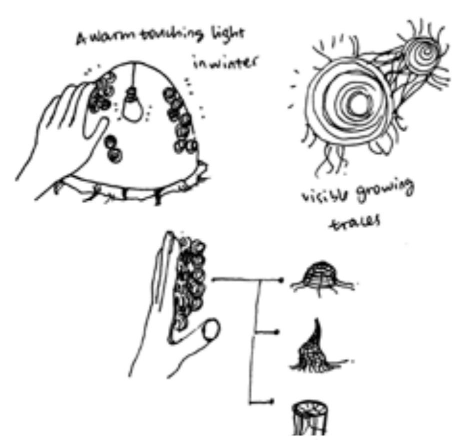
Concept A Keyboard

With this concept, a keyboard is grown by roots. The electronics are embraced by roots in the growing process, therefore becoming a robust whole. The keys are grown in different templates, thus showing different morphology of root growth traces. It shows the strength by making people type, and surprise come when people find the pushing back force. By repurposing a growing material for digital use, this concepts emphasize the blurring of nature and the man-made world.



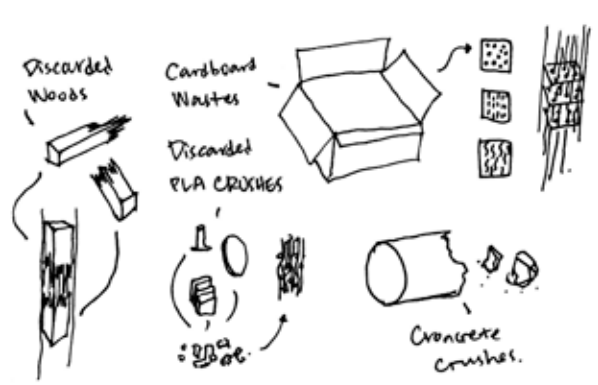
Concept B Warm Touch Light

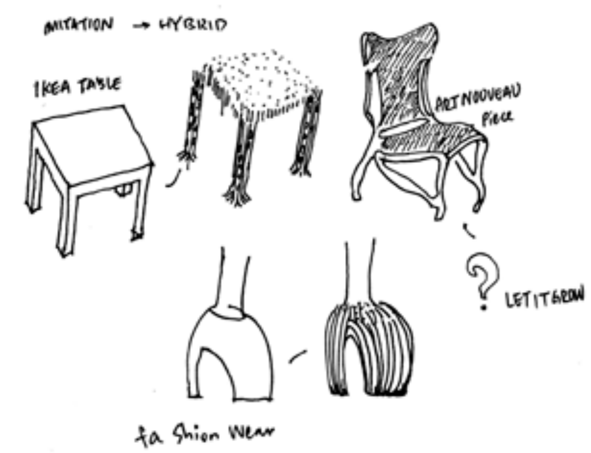
This concept emphasizes the warmth of the material and fascination in touching the patterns. Light is used to present the intricate patterns more clearly and emphasize on the growing traces. The surface pattern can be in different forms, which trigger different interactivity.



Concept C Repairing System

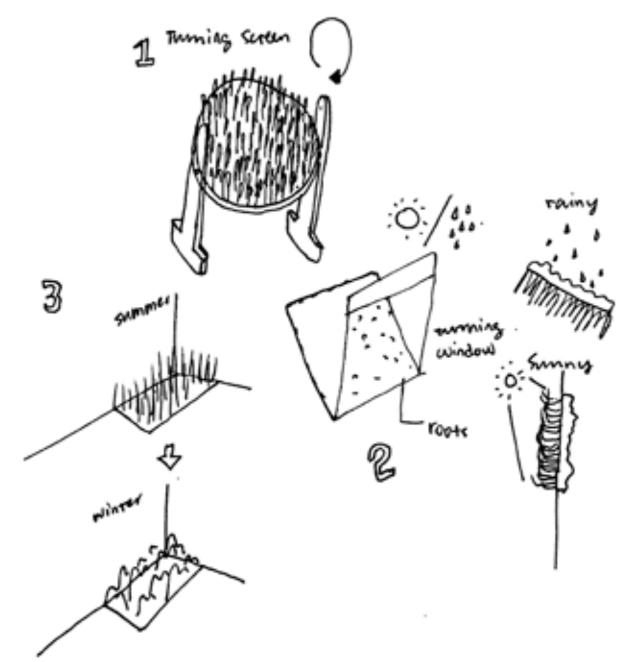
Many porous structures can be repaired by roots. A repairing system can be developed, based on roots' ability to glue broken parts. Discarded materials like wood, concrete, PLA, cardboard, can be re-design to satisfy roots needs of growing through them and co-created new materials.





Concept D Remix Archetypal Products

Imitating archetypal products triggers people to make comparison between the two products. In order to emphasize on the strength and hybrid feeling, the most iconic mass-produced products are imitated. In this way the border between nature and the man-made is blurred and people get to experience the strength of the composite.



Concept E Turning "Rootscape"

Turning "Rootscape" means a turning board made of growing roots and grasses at each side, that can be turned due to needs. For instance, when it is raining, the root side get upward; when it's sunny, the grass side gets upward. This interaction is very dynamic and show the growing process as a landscape.

FINAL CONCEPT: INTERWOVEN REMIX

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Roots Remixing IKEA ALSEDA

A banana leaf puff as an iconic product from IKEA is chosen as the man-made object to be imitated. In order to emphasize on the conflict. The reasons of chooseing ALSEDA are as follows:

Reasoning

- The height of growing of roots limit the product (or components) to be less than 100 mm. Growing components and then connecting components is possible, but it undermines the concept of growing an end product at once.
- Imitation as a concept would trigger curiosity in comparing the two products: appearance, sensory qualities, functionality, usability...in this way, people will spontaneous inspect the product.
- It is a non-expensive daily product and mass-produced furniture sold by IKEA, which is easily accessable by everyone. Imitating it means that root materials can also be used like it in a daily scenario.
- It is a product owned by someone, the strength could be shown by its durability.
- The ability to repair or connect porous parts is a unique feature of root growth. 3D printing technique can produce porous structures to purpose. For example, a skeleton or bone structure.
- The product is on a body scale, and the structure is suitable for resisting compressive force.
- A sitting puff can show both the body and skin of the material concept: body as functional support and skin as inviting elements.

Imitation

Form
The overall form of ALSEDA will be copied.

Pattern
The pattern of the banana leaves woven on the surface of ALSEDA will be copied by roots. The final result will not be identical to the original pattern, because roots have autonomy in forming their own growing traces in reaction to growing space.

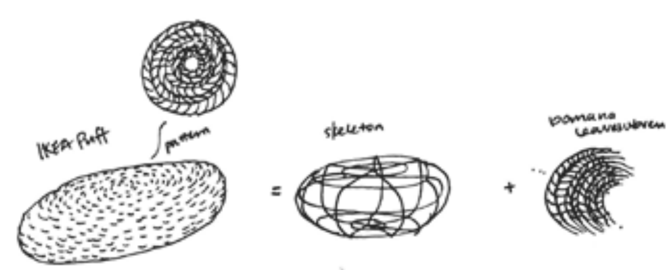

Figure [81]. IKEA ALSEDA stool

Case 1
The skeleton and half of the banana leaves are kept.

Case 2
Only the skeleton is kept.

Case 3
The upper half of banana leaves is kept.

Case 4
Only roots.

Case 5
Roots growing with porous structures. Nothing from ALSEDA is kept.

Case 6
Using topology optimisation to make the product more light weight and material-saving.

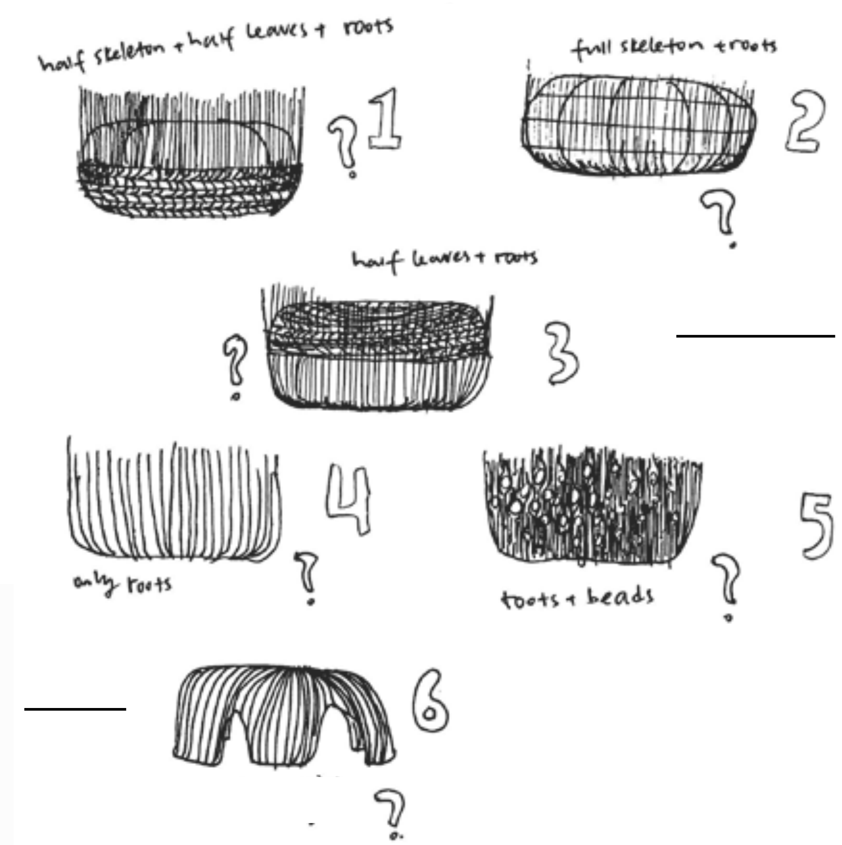

Figure [82]. Remix composition discussion sketch

Making Transition as Experience

To design a product is also designing the experience with which people encounter with the product. To emphasize on the remix effect, a group of products will be presented to the Audience. This is to create a transition effect between the objects: the original one as ALSEDA A, a remix ALSEDA B that tries to be identical, and a remix ALSEDA C that optimizes the shape of the ALSEDA.

Different compositions of ALSEDA B and ALSEDA C have been discussed as is shown on the figure above. Case 5 and Case 6 will be further designed and prototyped due to feasibility.

It has also been agreed by stakeholders that the design will keep the seeds and grasses in the product, which tell material narratives through the design itself.

SHAPE OPTIMIZATION

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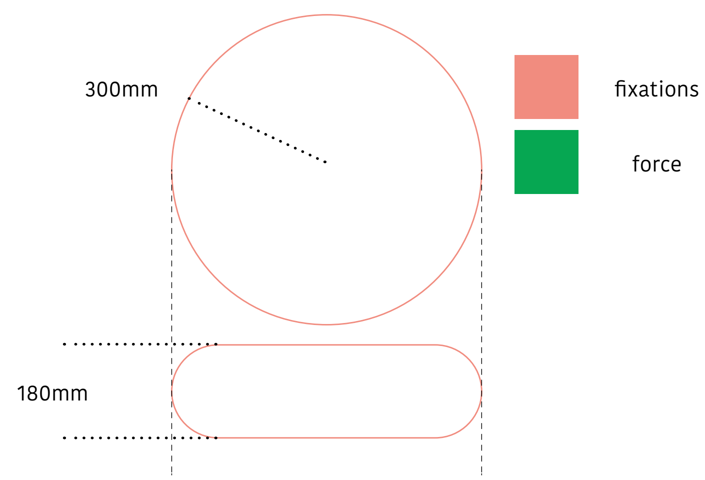
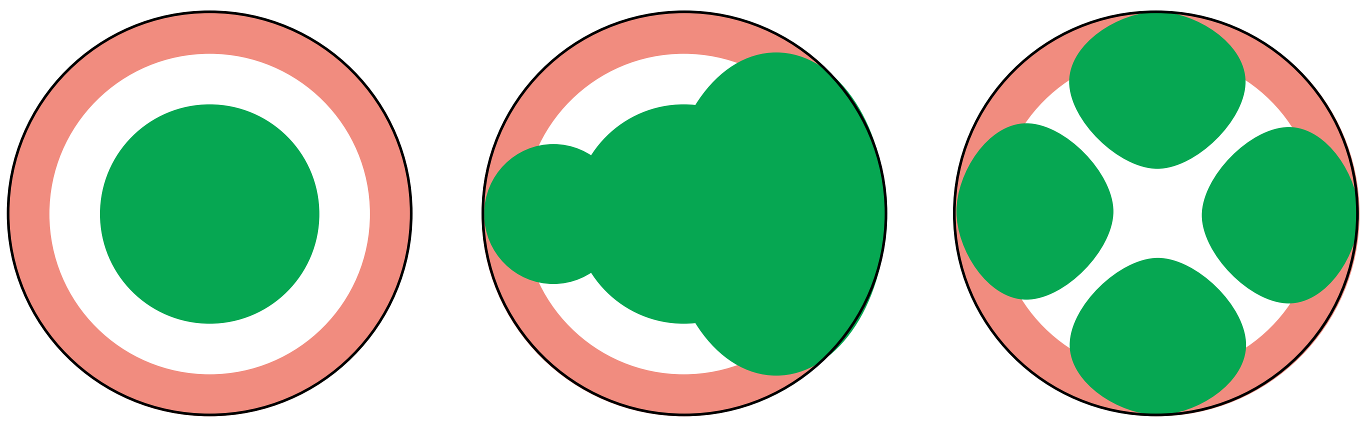
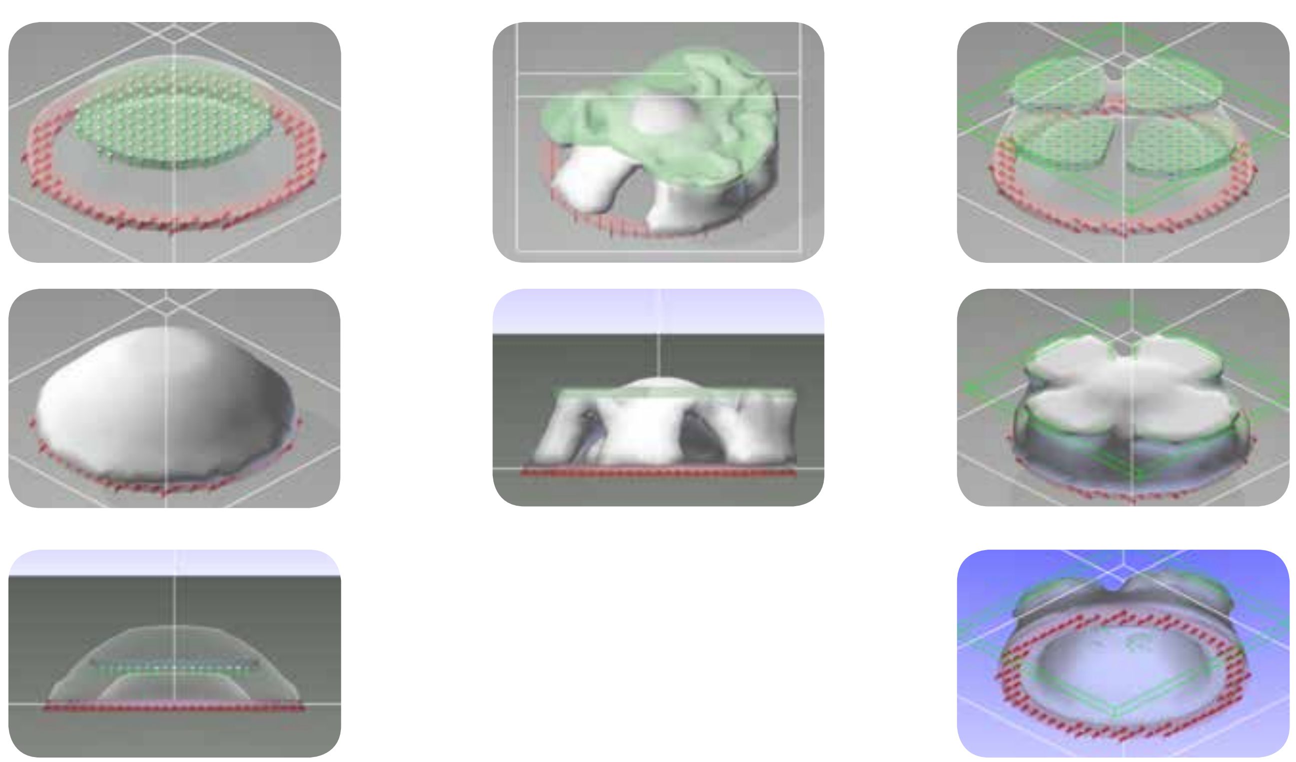
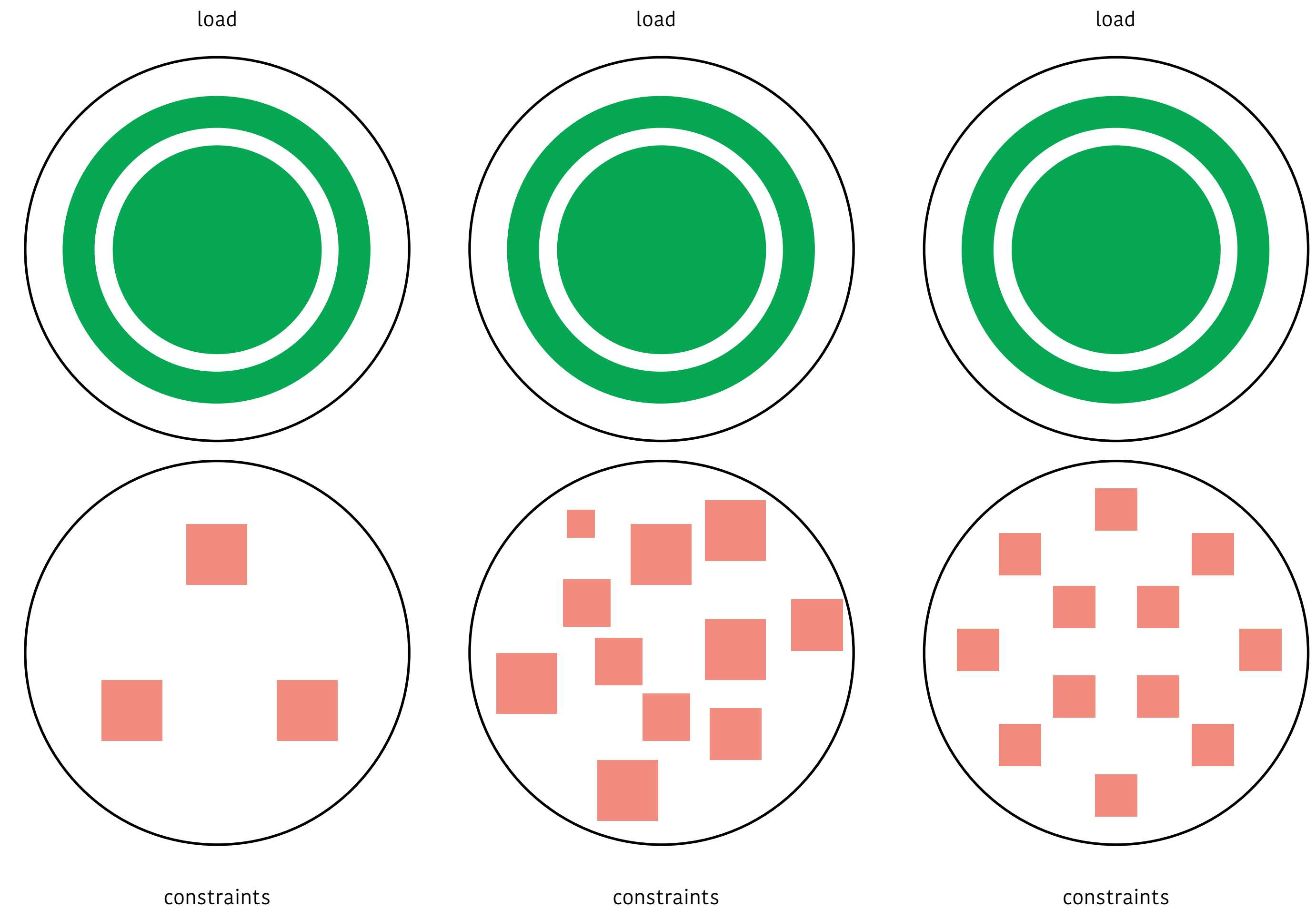
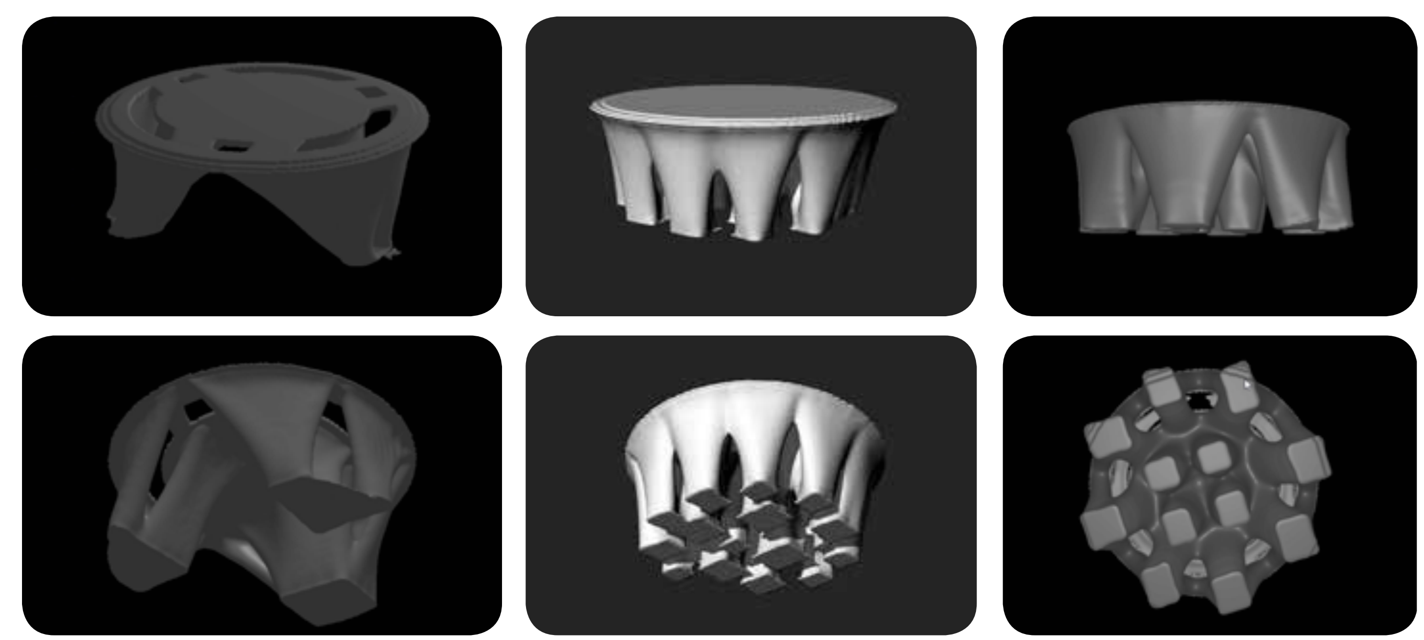
Using TopOpt 3D and GPU TopOpt softwares, several variations of force and fixation possibilities are explored, according to assumed using scenarios. This is to understand which parts of materials are essential to the load-bearing of the sitting object.











In the first round of optimization, load areas are experimented. Green areas mean load areas, red meaning fixations. The 1st load area is prefered because the idea of the stool is that people can sit wherever they want to, instead of defined areas.

In the second round of optimization, fixation areas were experimented. The 8 fixation design was chosen due to it requires roots to be mostly perpendicular growing and the growing vessel will be most conveniently produced by 3D printing.

Modifications to Fit Root Growth

In the previous tinkering process, it has been learnt that roots grow towards gravity. Therefore, if seeds are placed on the 'feet', they will only grow perpendicularly, mostly, then some space in the pillars won't be covered, as is shown by the illustration.

It is important to modify the generated form according to seed growing principles. So, from a 30% mass generated form, the pillars are enlarged to have straight borders. The cross-section shape is taken from the generated model. The leg height is 130mm. The sitting panel will also be thickend to at least 30mm and enable space for pattern forming.

Figure [83]. Analysis of modification to root growth

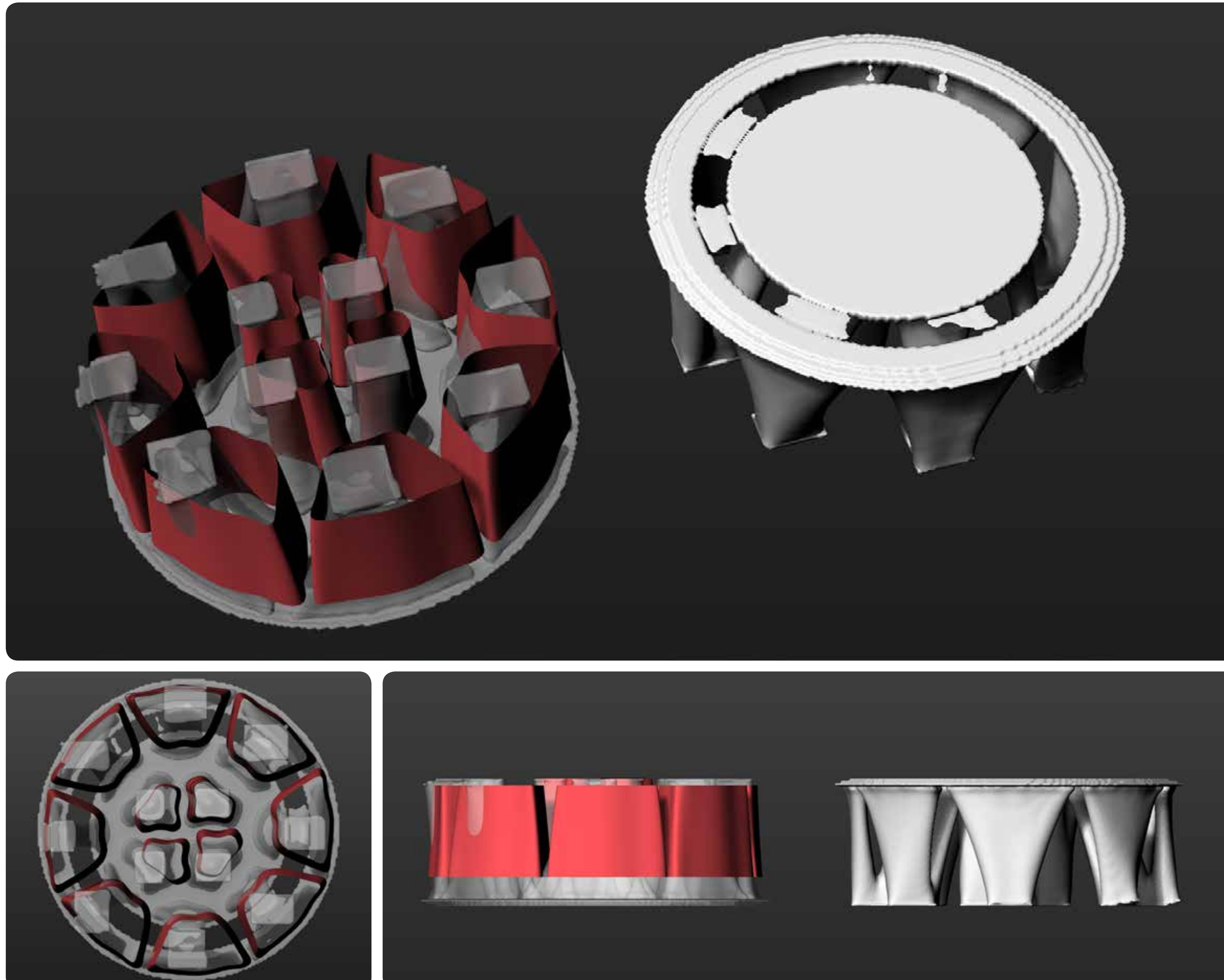


Figure [84]. Modification of the generated shape. Up: perspective view, left: bottom view, right: lateral view

‘BODY’ STUDIES

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Design Requirements

- allowing roots to go through easily: holes should be big enough (> 5mm) ;
- as many holes as possible to make sure roots reach the bottom of the container to get patterns
- the structure should not buckle easily when compressed
- should create a winding path for roots to increase the complexity of root- hair web
- light-weighted
- easily produced

Material Choosing

According to the following five aspects, PLA is chosen to be the material for making the porous structure. It is easily processed by 3D printing and easily made porous by modelling the structure. At the same time, PLA structure can be made very light, using certain structures. It is sustainable because it is a bio-plastic and can be degraded in 6 months in natural compost. Last but not least, PLA widely used in additive manufacturing fit the vision of hybrid of nature and man-made materials.

Material		Making Porousity	Easy Processing	lightness	Sustainable	Fitting Vision
Wood		●●●●	●●●	●●●	●●●●●	●●
Metal		●●●●	●●	●●	●●	●●●●●
Ceramics		●●●	●●	●●	●●	●●●●
PLA		●●●●●	●●●●●	●●●●	●●●●●	●●●●●
shell		●	●●●●●	●●●	●●●●●	●
stone/rocks		●●●	●●●●●	●	●●●●●	●
polystyrene		●●●●●	●●●	●●●●●	●●● (using the discarded)	●●●●●
paper		●●●●●	●●●●	●●●●●	●●●● (using the discarded)	●●●
sponge		●●●●	●●●●●	●●●●	●●●●●	●

Figure [85]. Evaluation of different materials for porous structures

Micro Structure


Bone Structure


Lava Stone


Sponge


Elastic


Single hole


Small solid

Porosity decides the density of roots reaching to the bottom of the growing vessel, which will then influence the clearness of patterns. Therefore, the design of micro structure should allow as many roots as possible to go through easily. Natural matters like sponge and lava stone have porous structure, but the pores are not through. Bone structure is believed to be the most strong and light weight at the same time.

Porous Units

What shape is the porous unit? A discussion is shown on the figure [86].

Porous long pillars will give large support for the composite structure to resist compressive force from top down, because the pillars will take most of the stress. However, this strategy undermines the expression of sewing ability of roots by providing already supportive structures to the composite.

Oval shape may provide more stability when being compressed, because the beads compress each other mostly also in the perpendicular direction. However, the beads may need to be placed in the right arrangement as the graph shows.

Spine shape also need to be placed manually, which reduces the efficiency of making process.

Round shape is chosen because the units can be placed randomly in the growing vessel, with shaking well before planting. Visually, they are coherent to the material concept sample. And they show the sewing ability of roots well.

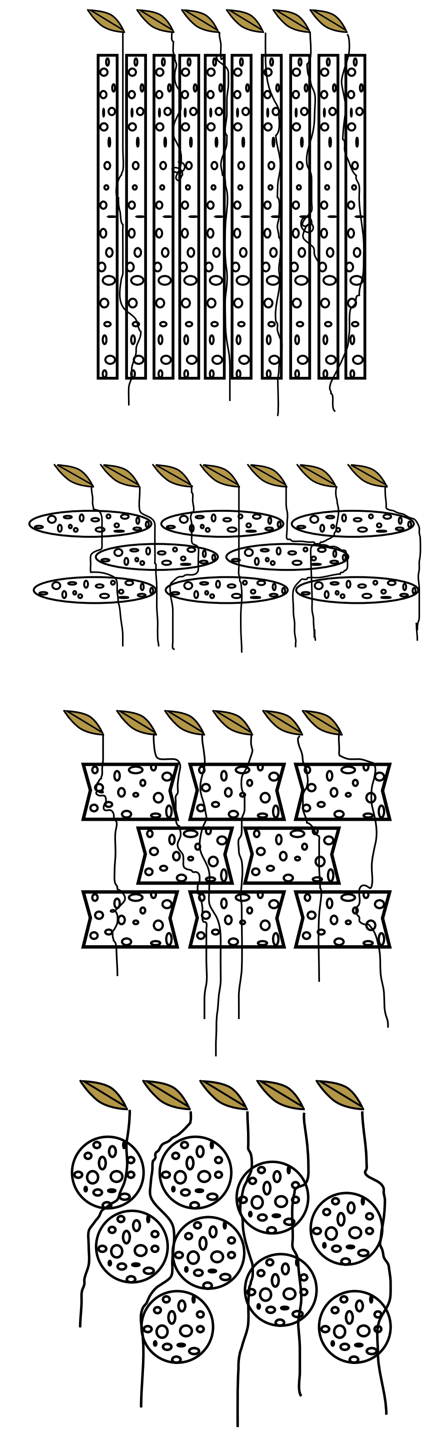


Figure [86]. Porous unit shape discussion

Bone Structure I - Radiative

As a result of porous structure studies, first iteration of porous unit is made and tested. Three sizes have been made: 10mm, 14mm and 20mm, but since the 10mm ones are almost impossible to be printed properly using Ultimaker 2+ in the faculty and it takes forever to take off support material, it is abandoned. The 14mm and 20mm units are then sewn by roots into cubes of 40mm by 40mm by 20mm. The 20mm unit is scaled 3D from 14mm.

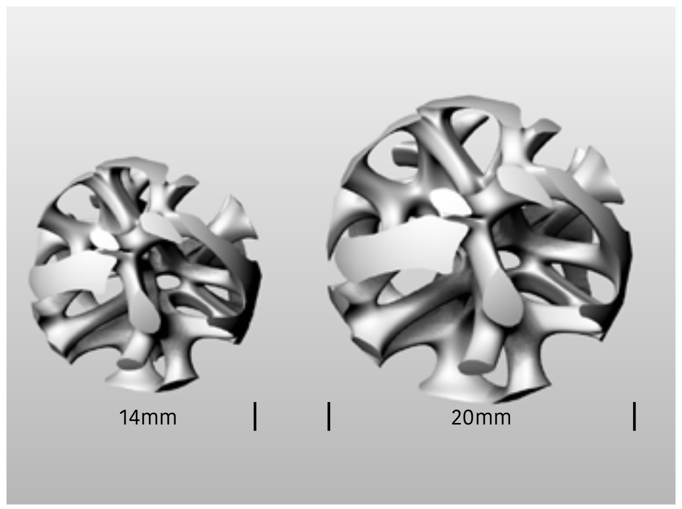


Figure [87]. Radiative bone structure units of 14mm and 20mm

Figure [88]. 14mm units sewn by roots

Figure [89]. 20mm units sewn by roots

Compression Test

Samples
The samples shown in Figure [90] are from left to right: naturally grown, samples with 10 pieces of 14mm porous bone structure beads and with 6 pieces of 20mm bone structure porous beads.

Each sample is individually grown at the same time from one batch of seeds to ensure equality. The growing form is a 40 x 40 x 20 mm cuboid, but all samples shrink to a smaller size; composite samples shrink less severely. For the test, the height, width and length of each sample is individually measured.

Method
The test uses a ZWICK machine with 10kN load cells. The test takes reference of ASTM D6641, but many parameters are adjusted to fit the material in use. For instance, the compression speed is adjusted to 5mm/min, according to a trial test in advance. Each test is conducted three times for one type of material.

Results
The figures show graphs of the natural, 14mm bead and 20mm bead samples stress/strain curves. Compressive strength is compared at the apex before the curve goes down and then dramastically up again. This apex means the maximum stress the material can resist before failure.

The natural samples has an average maximum stress of 0.014Mpa; 14mm samples 0.57Mpa; 20mm samples 0.27Mpa.

After failure, the curves in 20mm samples all go dramatically up, which mean that the load is all on the PLA structures.

Discussions
Adding PLA structures definitely increase compressive strength. Roots as glue bind the structures well. All the fractures happen locally without breaking the cubes totally.

The 14mm samples resist largest stress, probably because the units have better interlinks, but causes can be unknown.

The decisive compressive stress of the composite structure is finally caused by PLA structures. Loser structures allow more space for roots to move and

Figure [90]. Compression test samples, from left to right: naturally grown, with 10 pieces of 14mm beads, with 6 pieces of 20mm beads

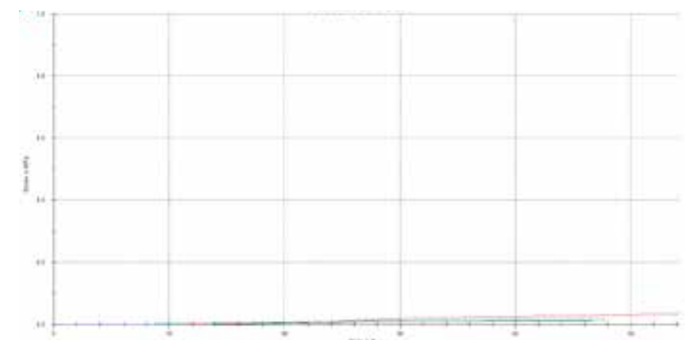


Figure [91]. Test results of natural samples

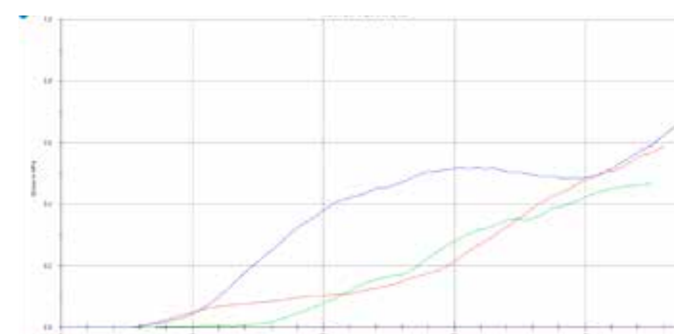


Figure [92]. Test results of 14mm composite samples

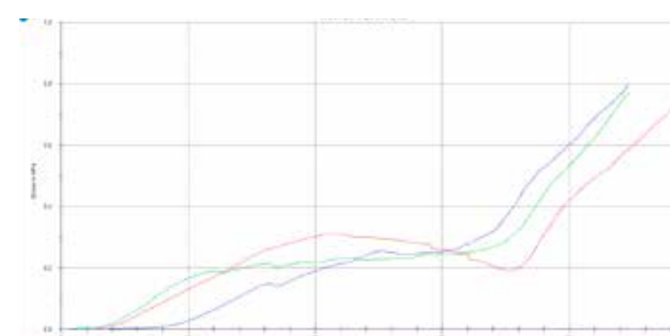


Figure [93]. Test results of 20mm composite samples

buckle. The radiative bone structure is thought to be too stiff and uncomfortable as interface for sitting. The next step is to design the unit to have more interlinks and less stiffness.

Microscopic Examination

From images of microscopic observation, the composite structure is made up of roots, massive root hairs, and PLA. It is clearly seen that roots go around PLA. Root hairs are almost everywhere, forming a complex web.

It could be concluded that roots and PLA are spontaneously collaborating to form a organic whole that serves similarly to a compund material like carbon fibre x resin, reinforced concrete, fibre-reinforced resin, etc.

Figure [94]. The composite structure under microscopy

Bone Structure II - Shell

Insipiration - Kunstformen der Natur

Kunstformen der Natur (known in English as Art Forms in Nature) is a book of lithographic and halftone prints by German biologist Ernst Haeckel. Originally published in sets of ten between 1899 and 1904, it consists of 100 prints of various organisms, many of which were first described by Haeckel himself. Over the course of his career, over 1000 engravings were produced based on Haeckel's sketches and watercolors; many of the best of these were chosen for Kunstformen der Natur, translated from sketch to print by lithographer Adolf Giltsch. The over-riding themes of the Kunstformen plates are symmetry and level of organization. The subjects were selected to embody these to the full, from the scale patterns of boxfishes to the spirals of ammonites to the perfect symmetries of jellies and microorganisms. Kunstformen der Natur was influential in early 20th-century art, architecture, and design, bridging the gap between science and art. In particular, many artists associated with Art Nouveau were influenced by Haeckel's images.

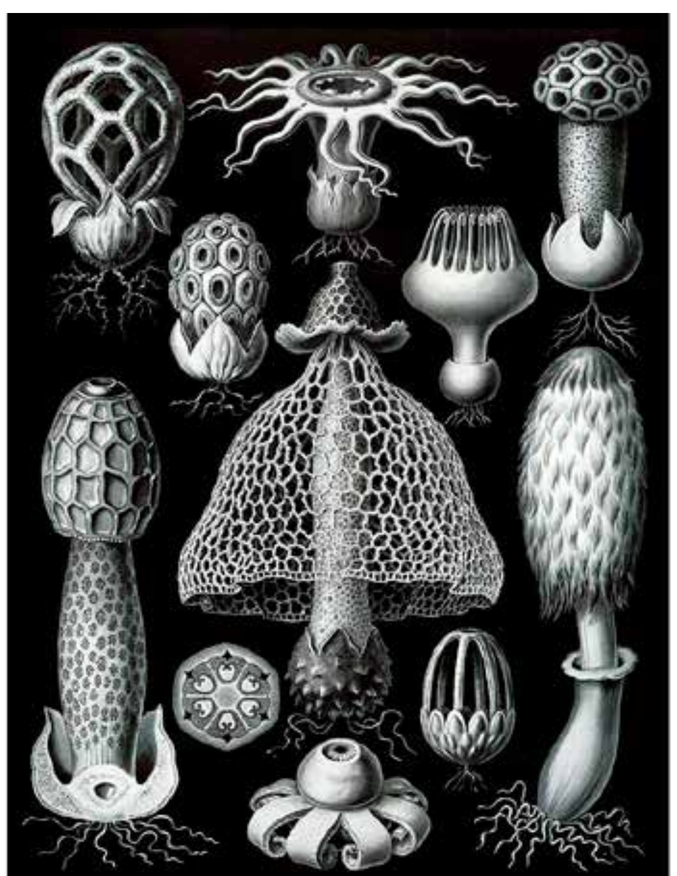


Figure [95]. Inspiration from Ernst Haeckel. Image adapted from Kunst der Natur.

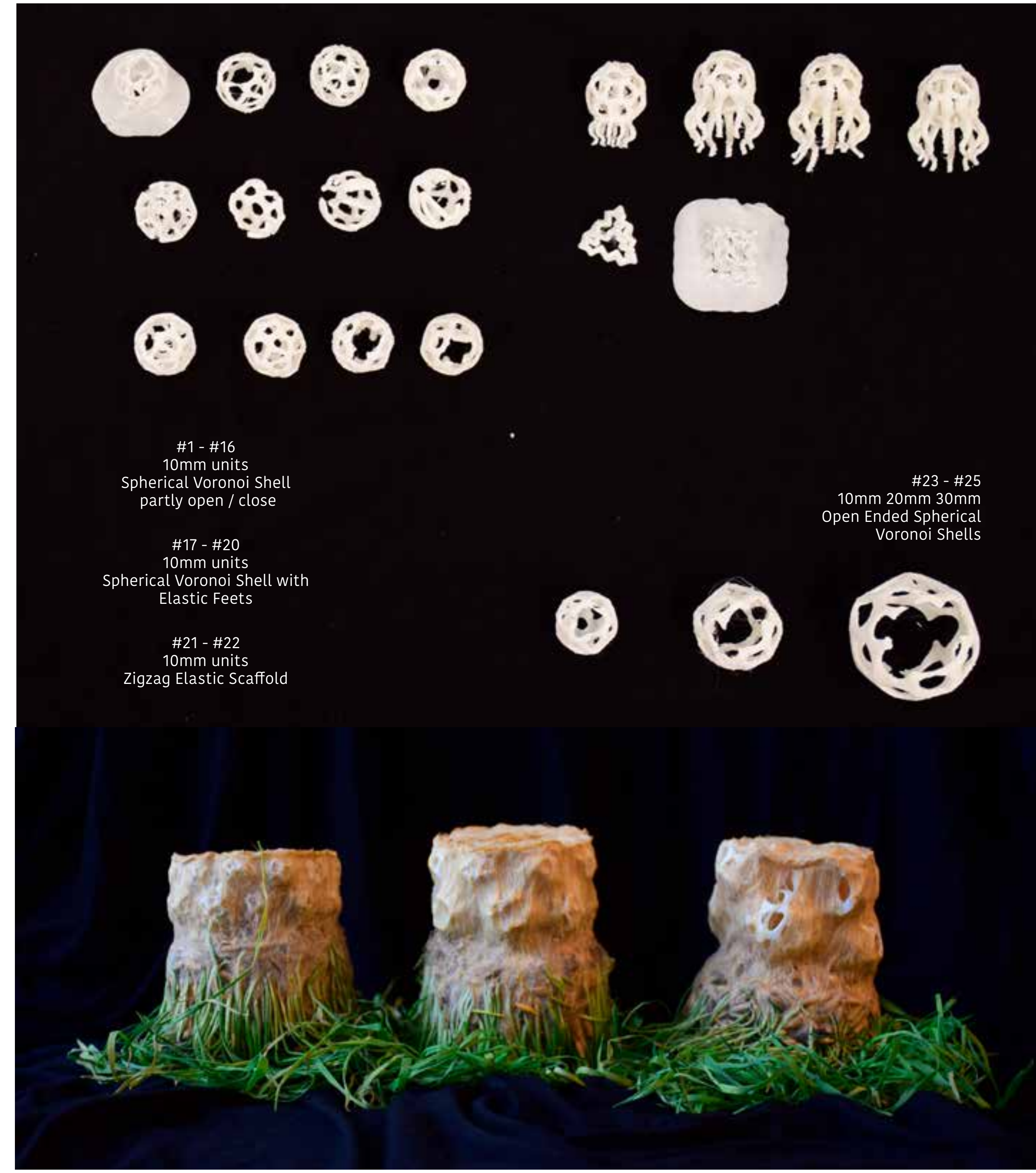
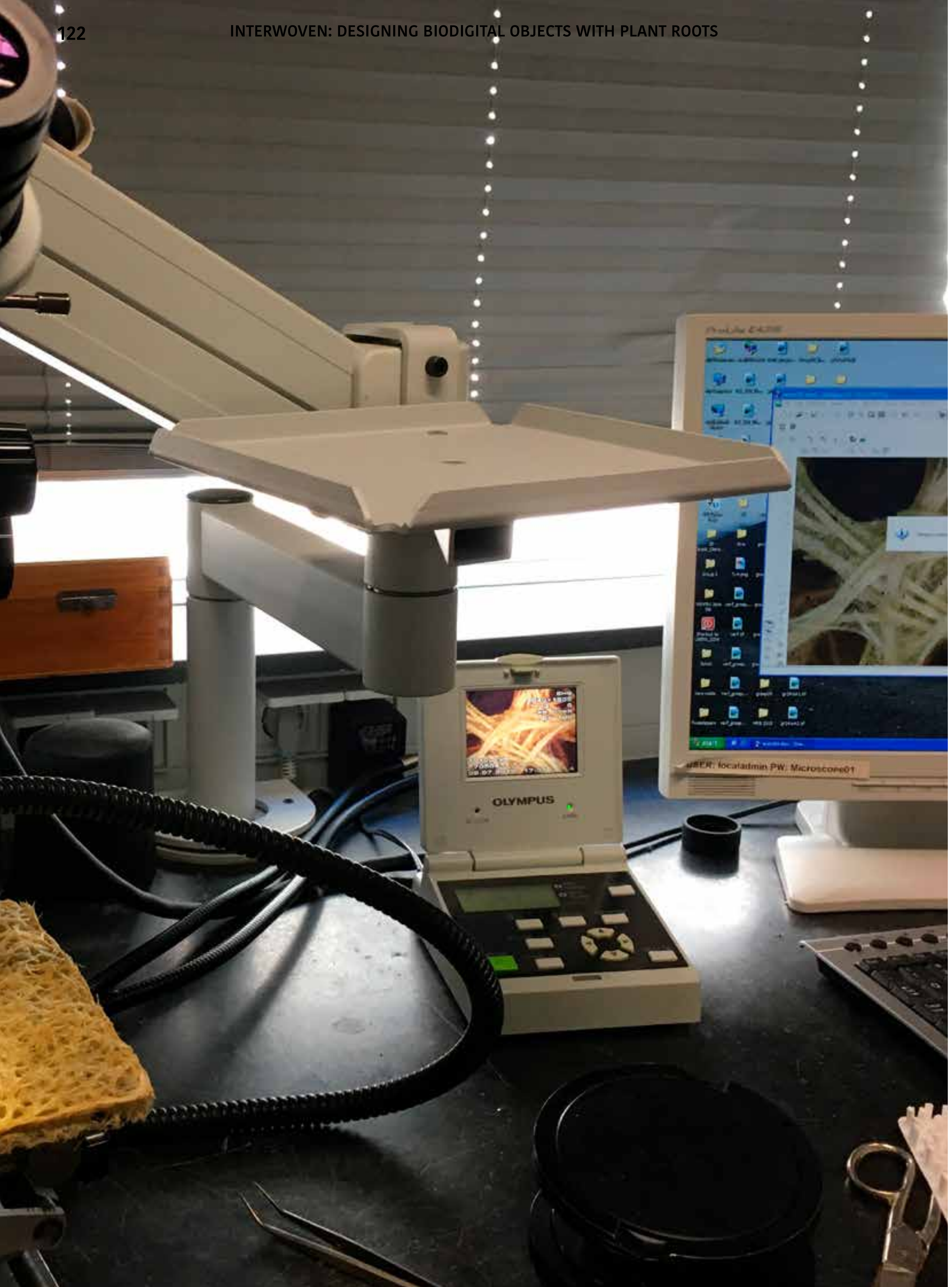


Figure [96]. Print tests for porous structure

Print Tests

Learning from Ernst Haeckel, 25 prints have been made to test by handling, the strength, flexibility and porousity. From empirical intuition, #25 has been rated as the best amongst the printed ones for the final design of porous units. It has biggest holes, and most flexible structure one direction, and stiffness on the other direction. Another important reason is that it is most convenient to print using Ultimaker 2+ in our faculty. The 10mm and 20mm sizes are too small for printer nozzles to operate stably. It is a pity that no more tests are allowed due to limitation of time to know precisely the compressive strength of the composite structure, but 3 samples have been grown using the same structure but different sizes of units (10mm, 20mm and 30mm). By handling, they all feel quite comfortable and not so stiff.



'SKIN' STUDIES

-

Microscopic Examination

This study is to learn how the skin could very, by making roots grow in different space. It has been learnt by previous tinkering how the difference can be in shapes, but what about size and depth?

The microscopic test uses stereomicroscope with a magnification of 10 times. Using this magnification is to ensure that a holistic overview of structures and how roots arrange themselves can be seen. The figure below provides an overview of the process. Large prints will be shown in the next pages to show clearly the growing traces.

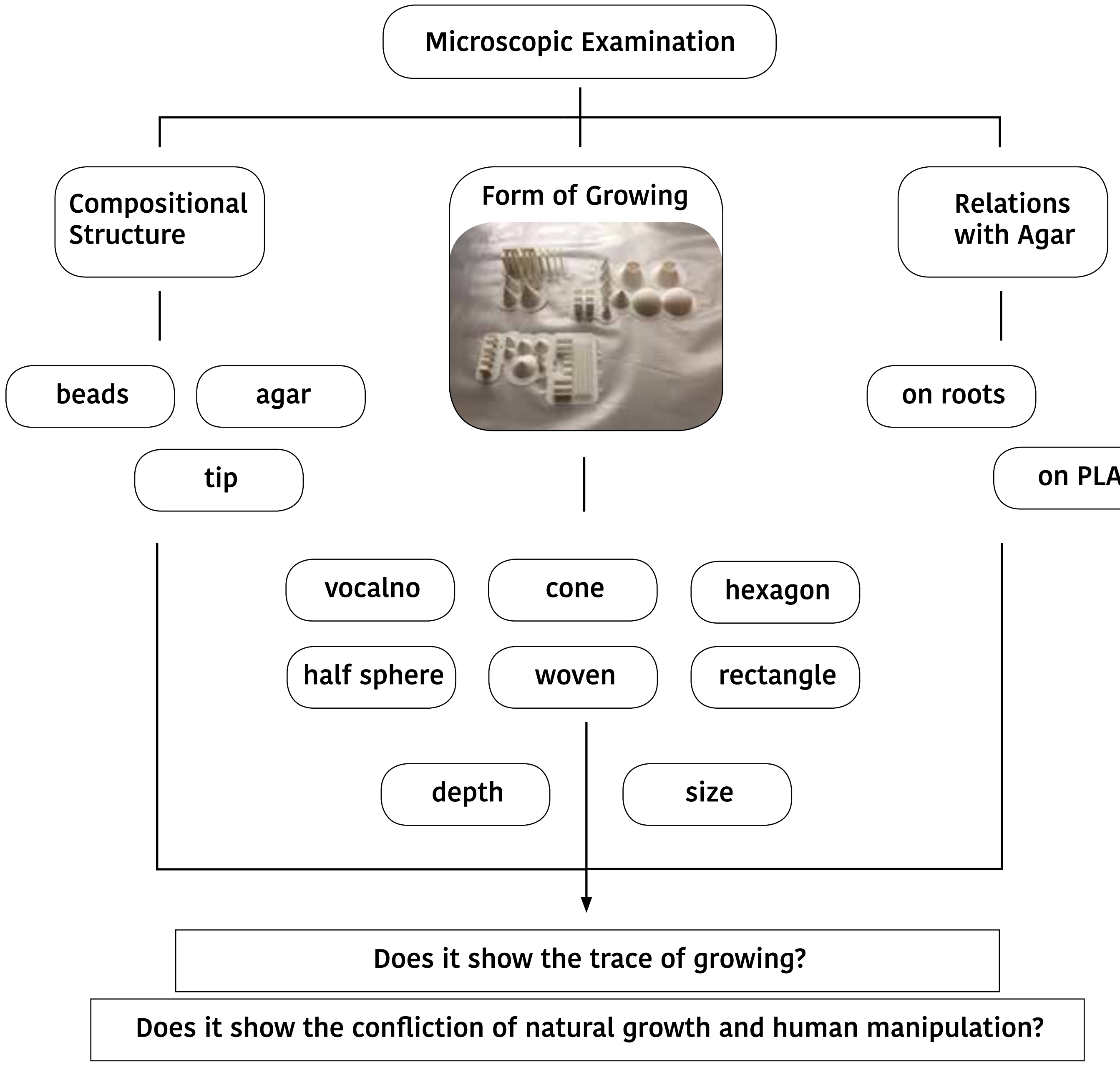
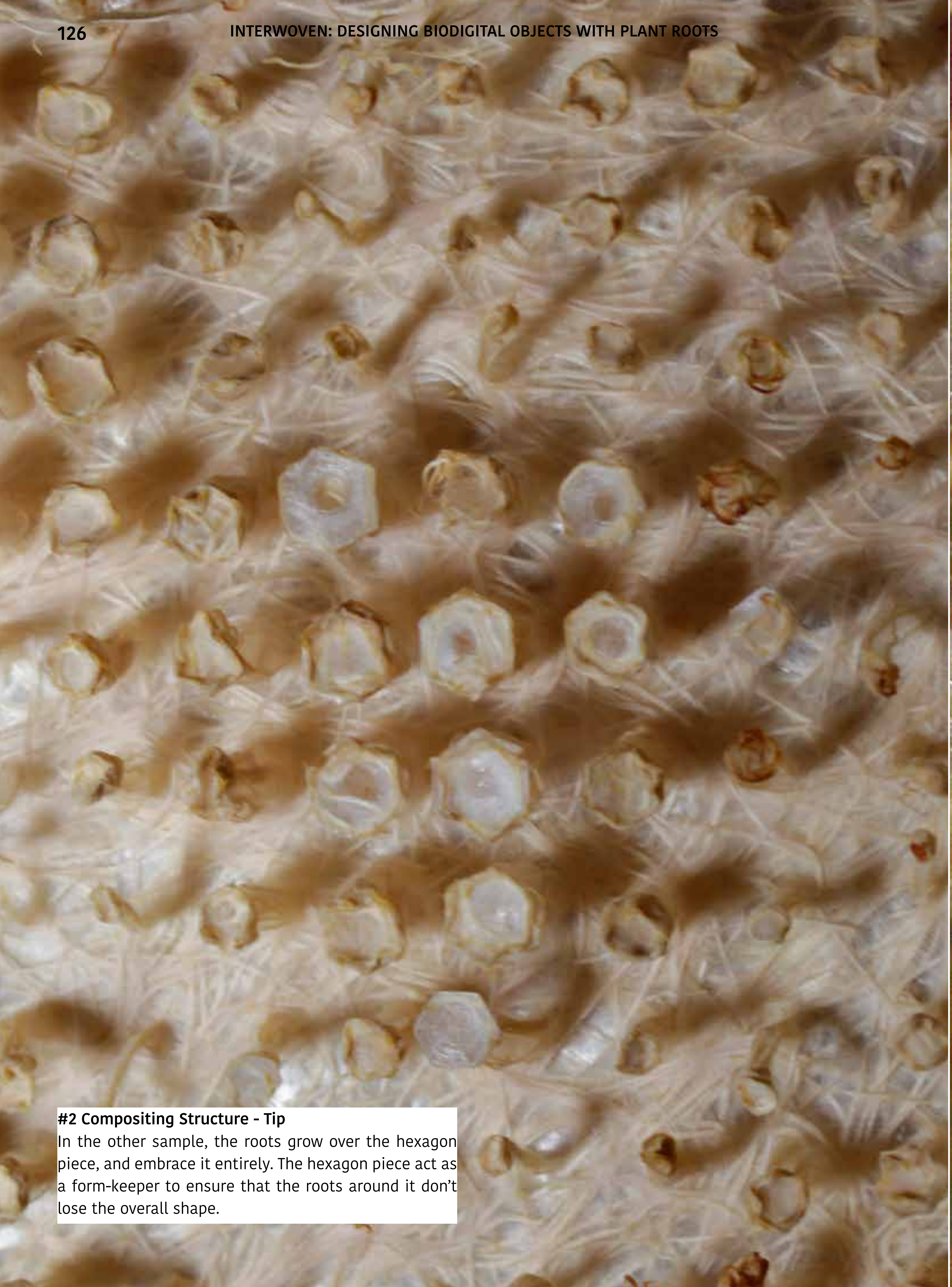


Figure [97]. Overview of microscopic examination

#1 Compositional Structure - Beads
There is one root going out of the hole in the middle of one bead. It is imaginable more roots and beads have this relationship hidden in the middle of the structure.

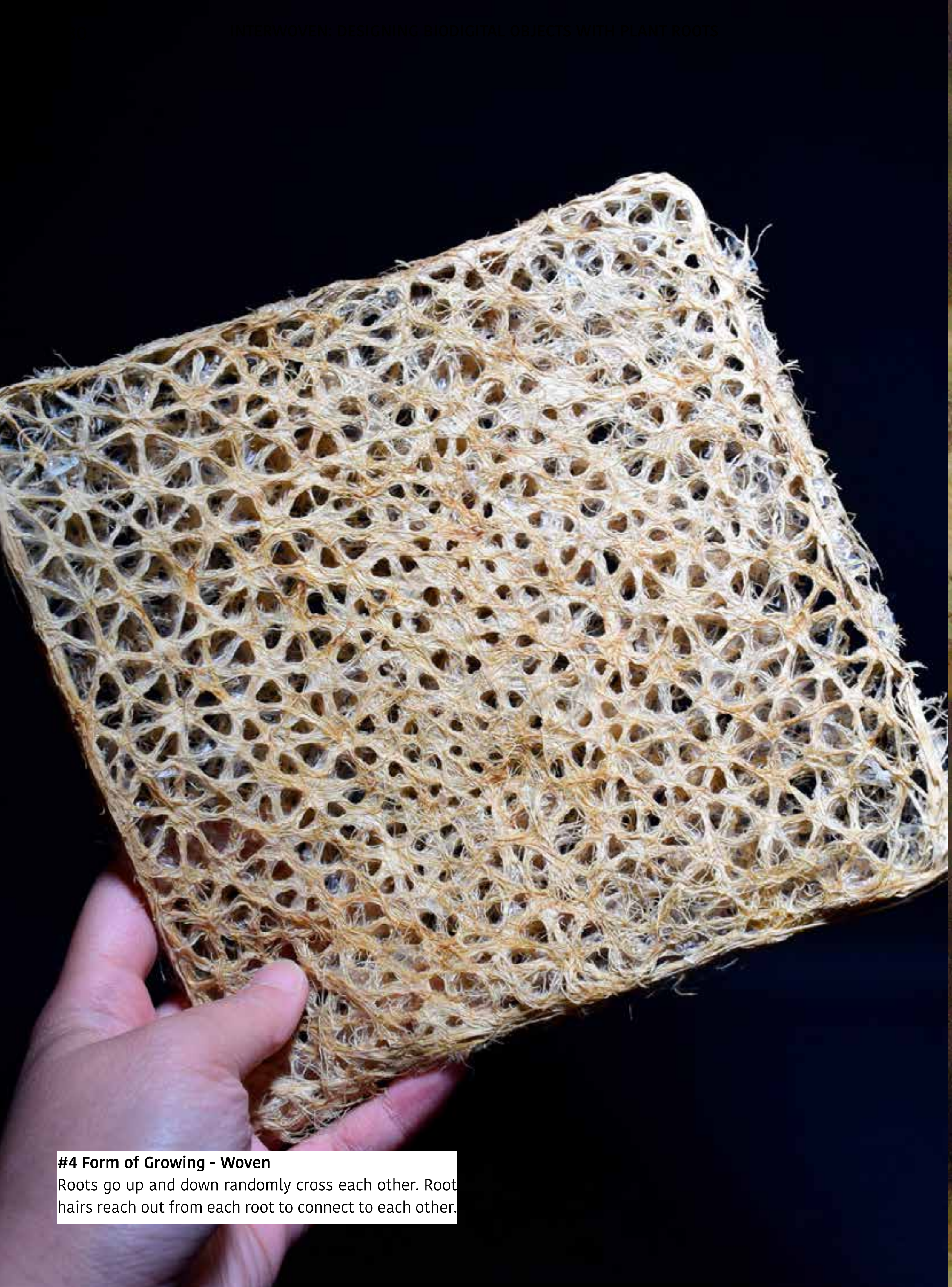


#2 Compositing Structure - Tip

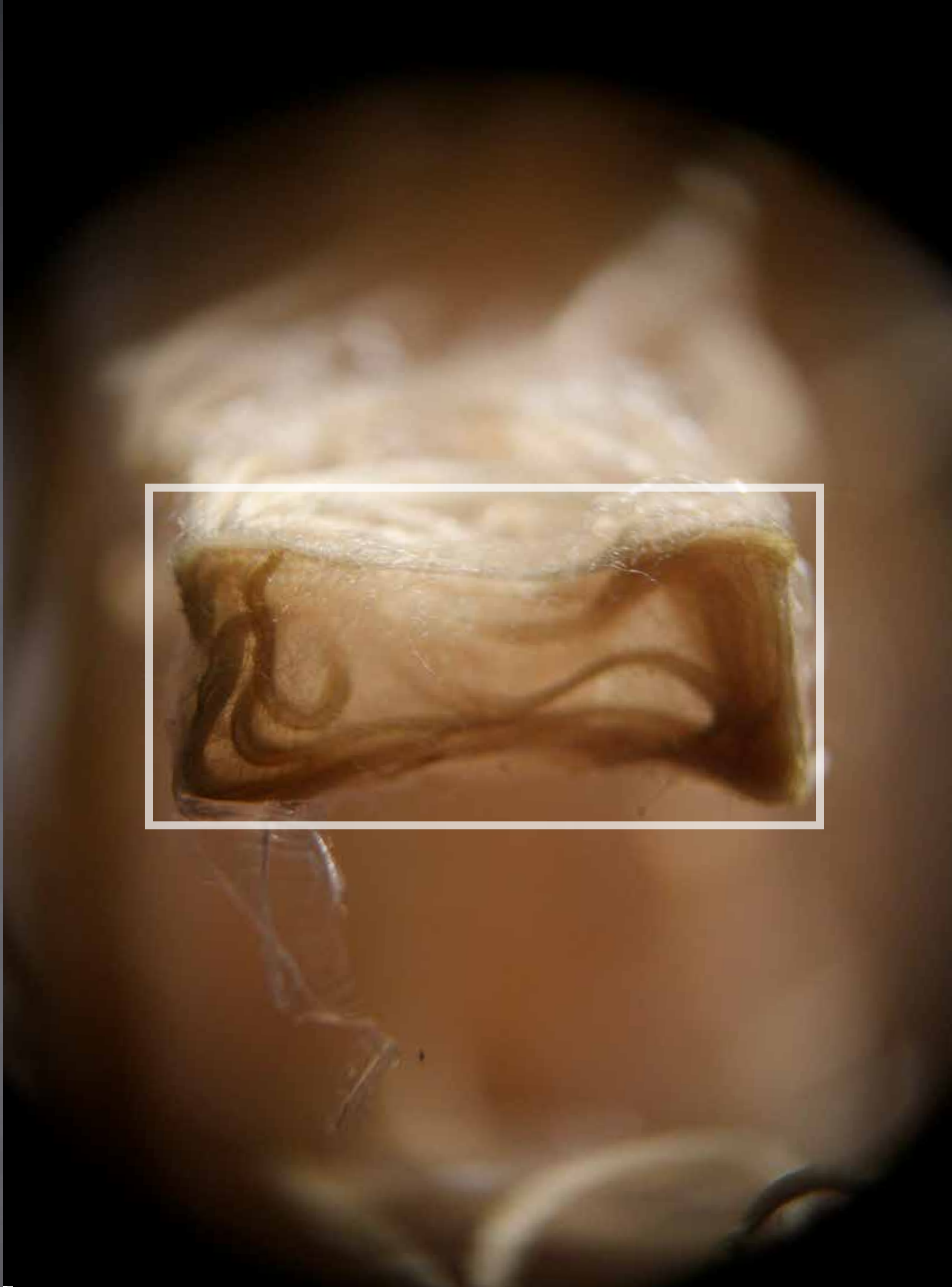
In the other sample, the roots grow over the hexagon piece, and embrace it entirely. The hexagon piece act as a form-keeper to ensure that the roots around it don't lose the overall shape.

#3 Composite Structure - Agar
The reflectional membrane in the image is assumed to be agar gel, which is the only added matter besides water and root nutrients. Roots seem to be embeded in the membrane without any sacrifice of their root hairs.

#11 Roots with Agar
This is the back side of a sample, where roots have been cut. It is clear that agar gel are small membranes in-between roots and are shiny due to light reflection.

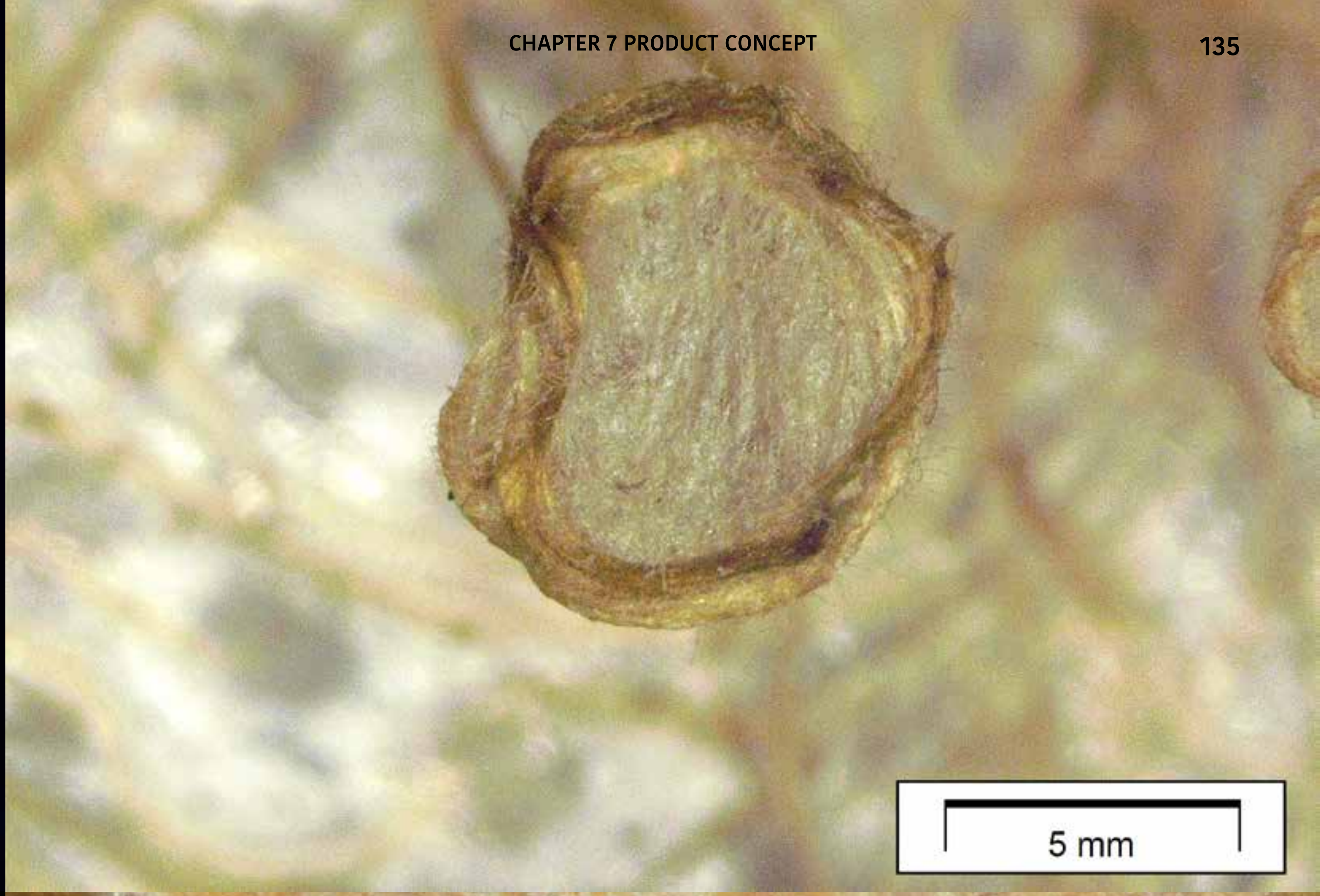


#4 Form of Growing - Woven
Roots go up and down randomly cross each other. Root hairs reach out from each root to connect to each other.

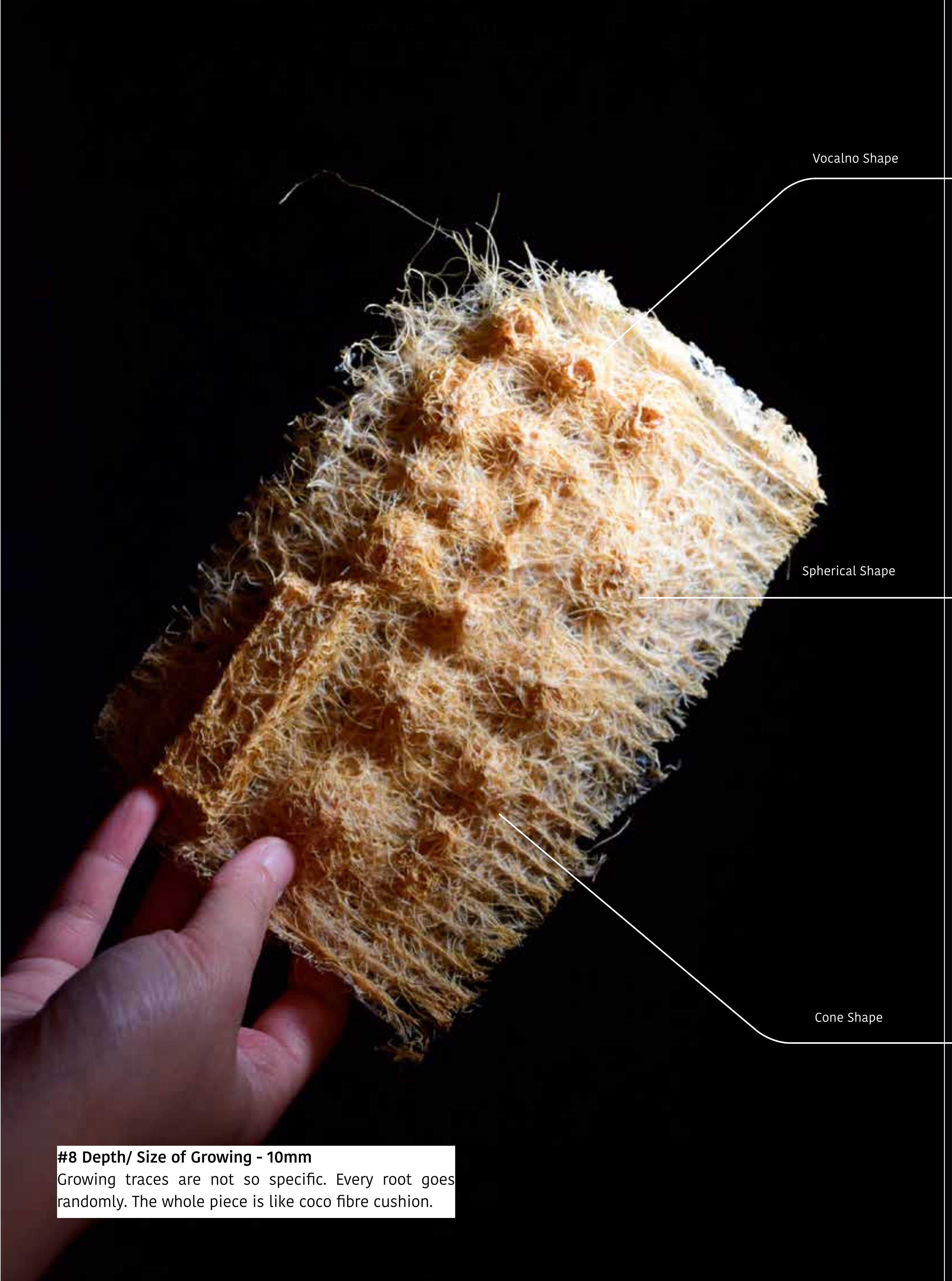


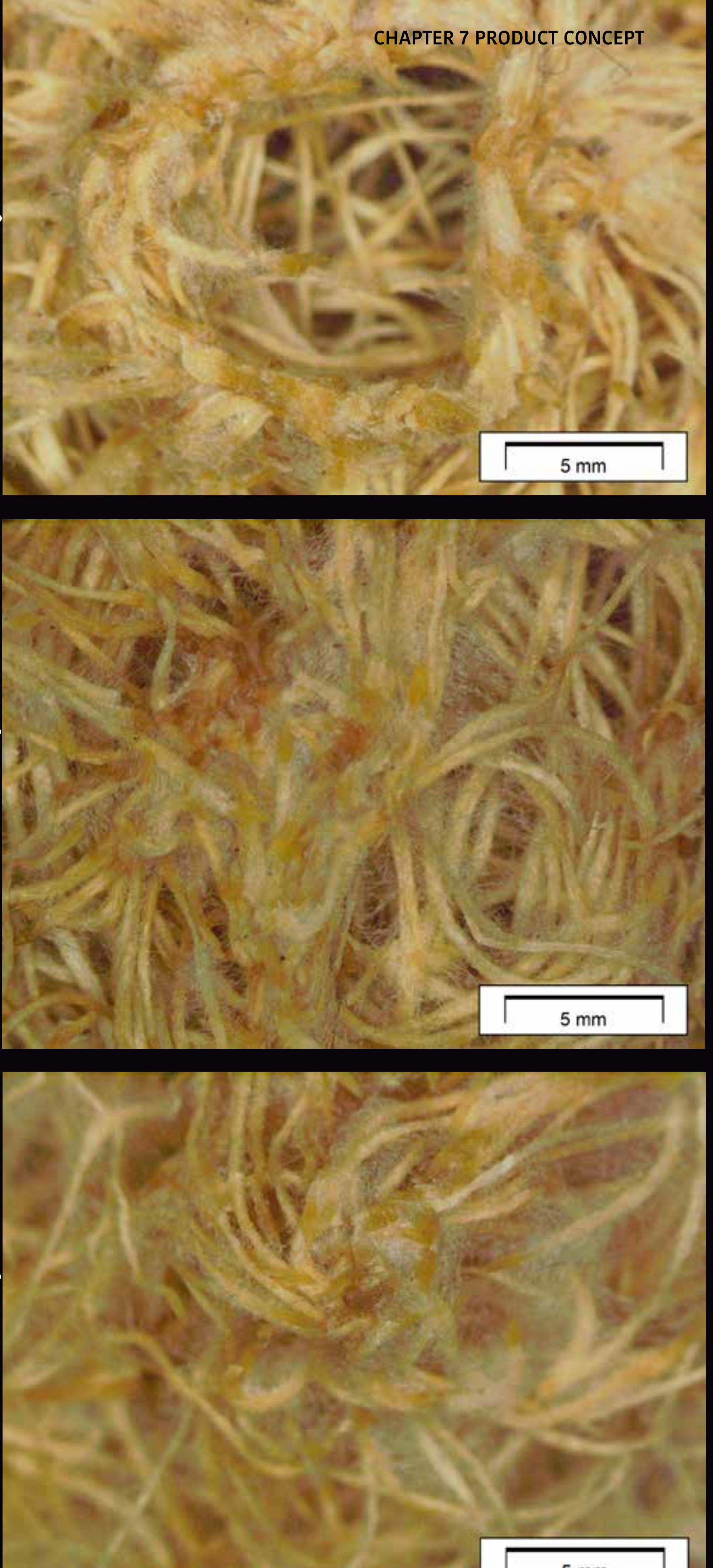
#5 Form of Growing - Cuboid
The micro image shows a shrivelled cuboid. Roots go around the perimeter more than across central area.

#6 Form of Growing - Hexagon on PLA Grids
No more like a hexagon. A flat round-ish piece with roots at the perimeter and root hairs in the centre.



#7 Form of Growing - Hexagon
Like a shrivelled fabric. The piece doesn't stand straightly as the piece above. More of a flower shape.





#8 Depth/ Size of Growing - 10mm
Growing traces are not so specific. Every root goes randomly. The whole piece is like coco fibre cushion.

#9 Depth/ Size of Growing - 20mm

Roots show difference in spherical and cone space. In spherical shape, roots go in circles, and in cone shape, they go in straight lines. The cone shape is curled.

#10 Depth/ Size of Growing - 30mm
A big hole is seen in the spherical shape in this size. The circling growing trace is visible.

PATTERN STUDIES

-

Unit & Pattern

The microscopic examination provides rich information and form languages for pattern design. Pattern is a repeating aggregate of each unit.

A field trip to Kew Gardens in London has enriched the collection of natural patterns as inspiration for the pattern selection. The collected patterns have been classified due to the known form that roots could grow in different shapes of growing vessels. (see Figure [98])

The selecting criteria is in close link to the design vision, which would invite people to inspect and feel the contradiction between nature and man-made world. According to this vision, the voronoi pattern with extruting units is selected. Voronoi shape is close to hexagon shape, and it ensures the pattern is most dense and without gaps between each other. It is a space saving solution. At the same time, the hexagon unit shows the growing trace very clearly. So will voronoi unit, as assumed.

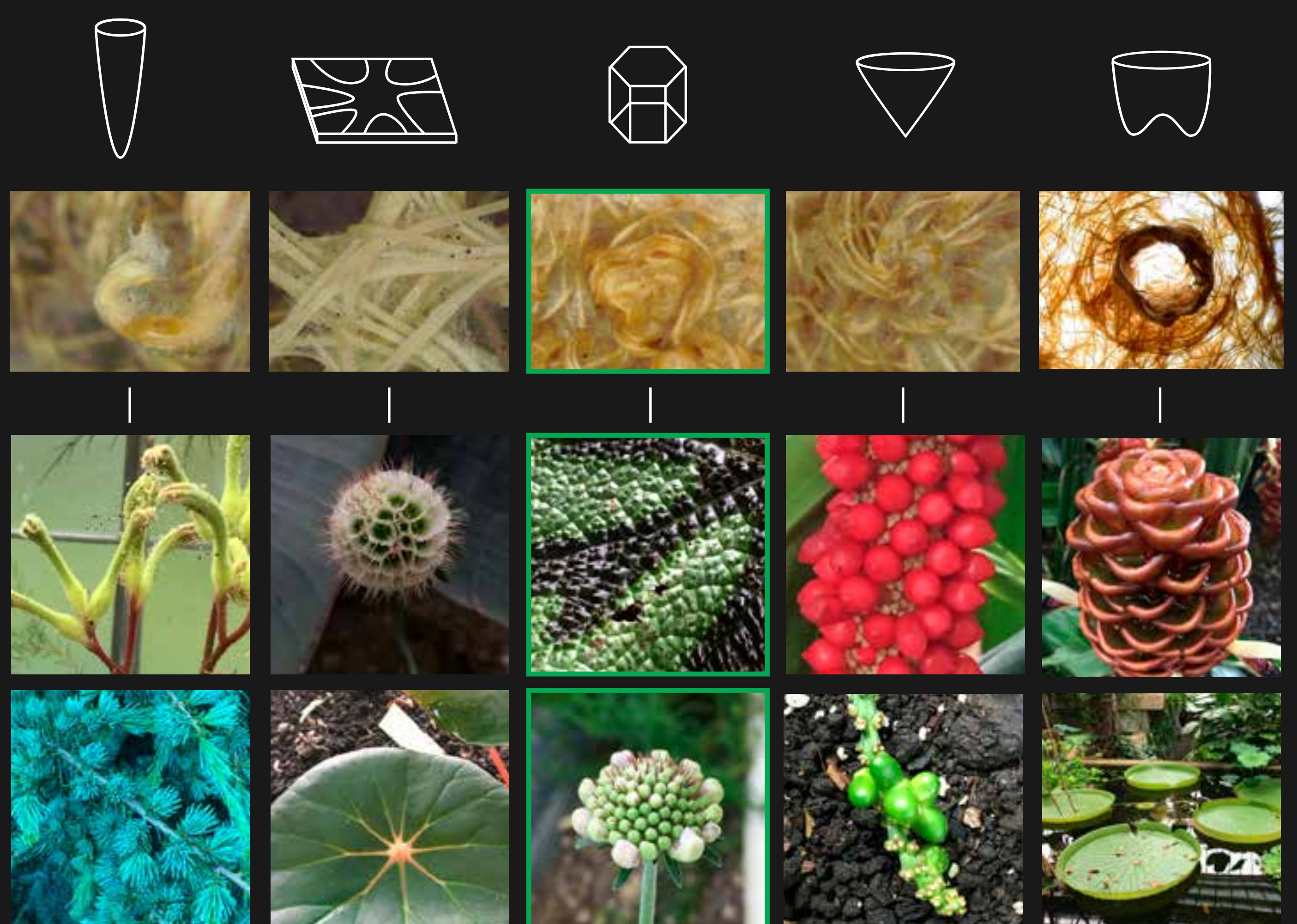


Figure [98]. Selecting patterns with extruding units

Size & Depth

As the evaluation (figure [99]) shows, the smaller diameter one unit has, the more visible is the trace of growing along perimeters of growing space. It is also shown that the longer extrutions are, with the same cross section area, the more obvious the natural shrinkage is, thus more visible is the conflict between nature and man-made world. A dense crowd of units and gradience are needed to show the conflict as well. However, growing depth is limited by the possible total growth of roots in a limited time and space. A test has been made to see how long roots can grow in two weeks (figure [100]). The tested plants are oat, corn and mung bean. It turned out that the oat is the plant which grew the longest within the same time, and with the best gravitropism effect, which makes the prototyping controllable. In two weeks they could grow to around 120mm, but most of roots stop at around 70-80mm. So the total height of each grown component of final prototype should be within this limit. Considering the total height of the final prototype, both pattern unit height and width are decided to be around 5mm. Due to necessary gradience, the biggest unit size should be less than 10mm.

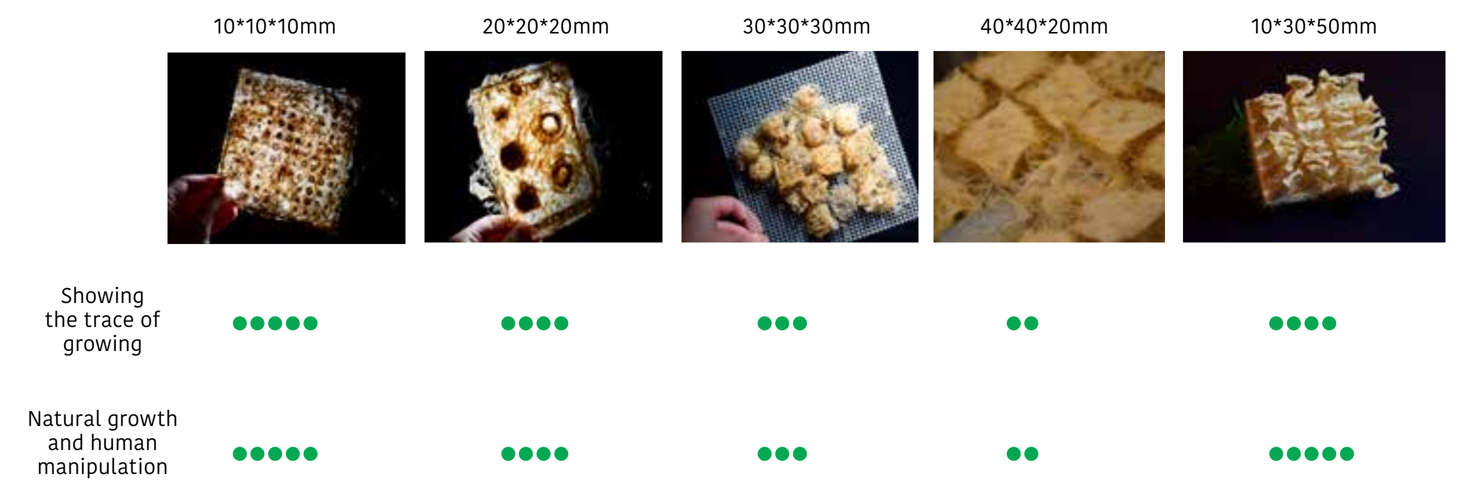


Figure [99]. Evaluation of extruding units of different size and depth

Figure [100]. Experiment about plant type and total growing length

Pattern Design

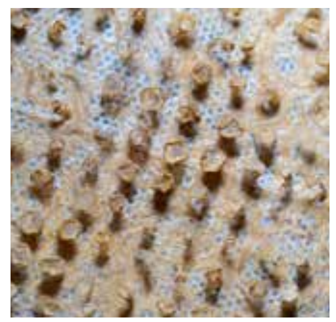
Pattern variations are created through Rhino and Grasshopper to choose from. The pattern design should take consideration of the following aspects:

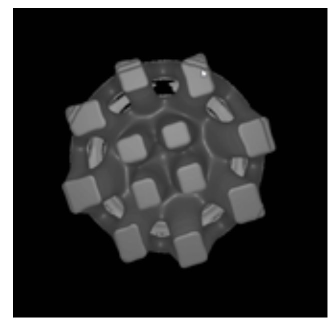
1. to reflect trace of growing, which represents organic autonomhy within human structured manipulation.
2. to invite people to touch and think through very precisely defined aggregates.
3. to create gradience, which makes people confused about whether the pattern is man-made or naturally grown.
4. to relate to the shape optimization.

As a result, #4 has been chosen to be the final pattern design, because it fits to the criteria best.


Trace of Growing


Voronoi Pattern


Creating Gradience


Shape Optimization

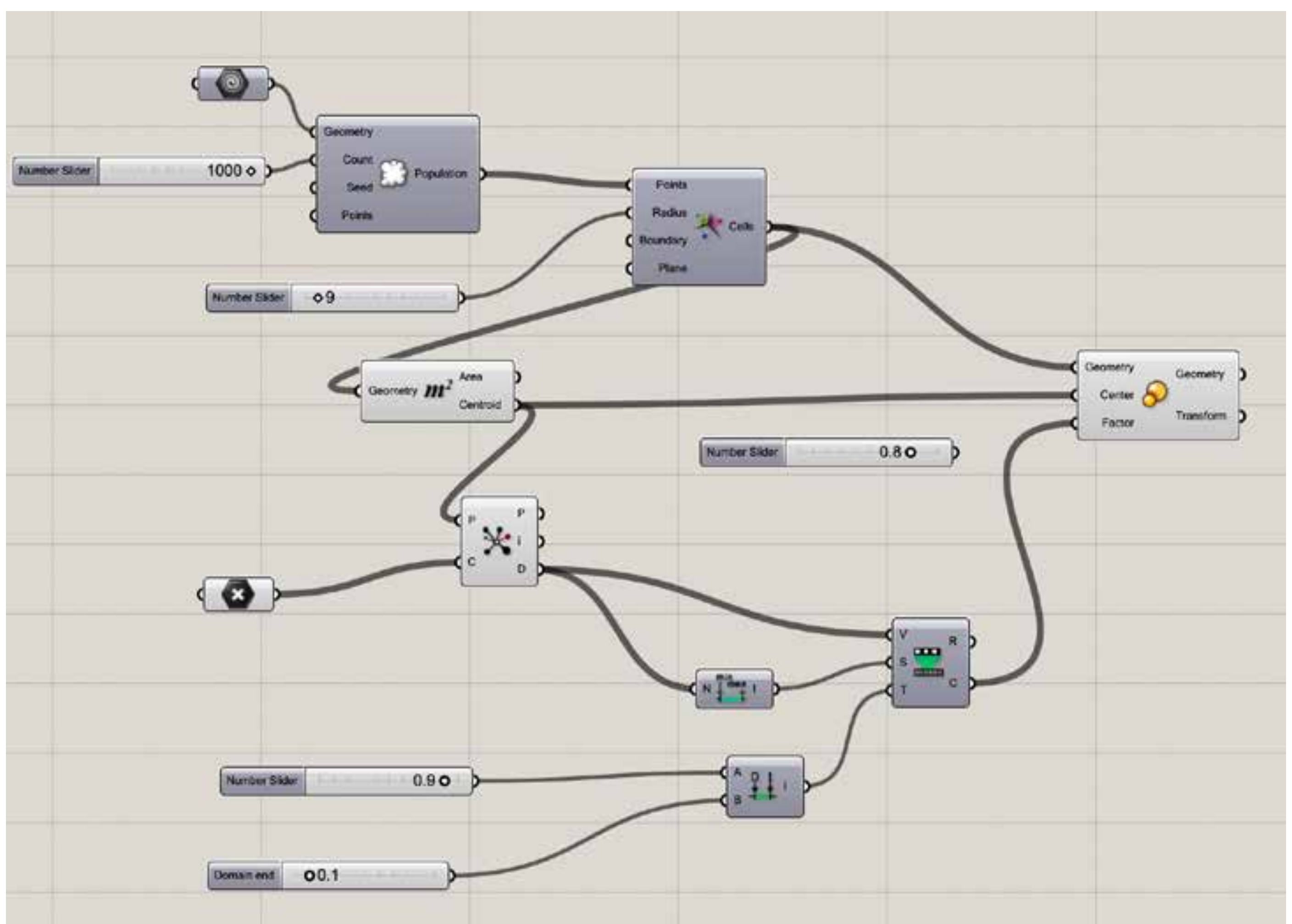


Figure [101]. Grasshopper programme to create pattern #4.

#1-#3 #4-#6 #7-#9

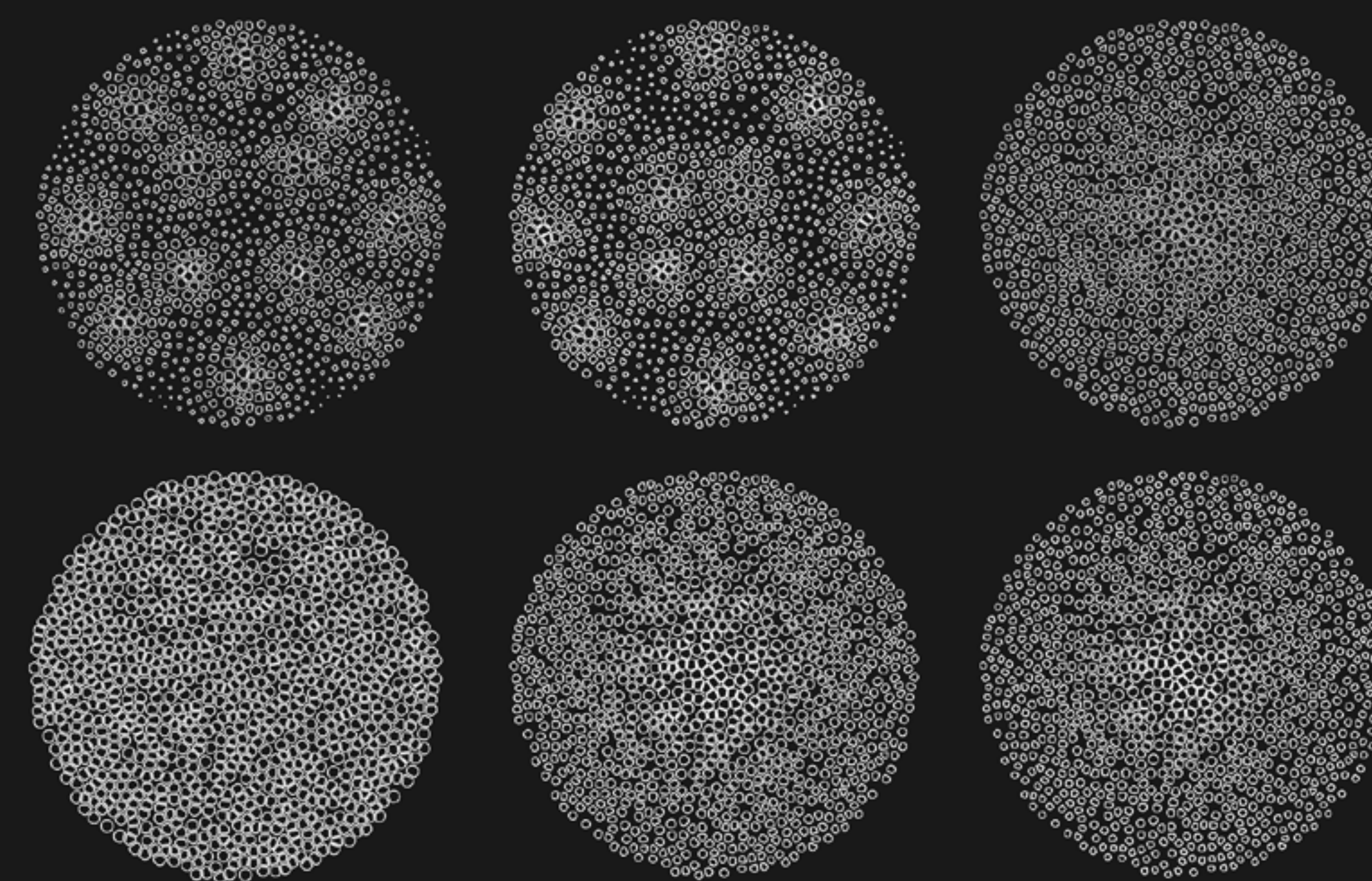
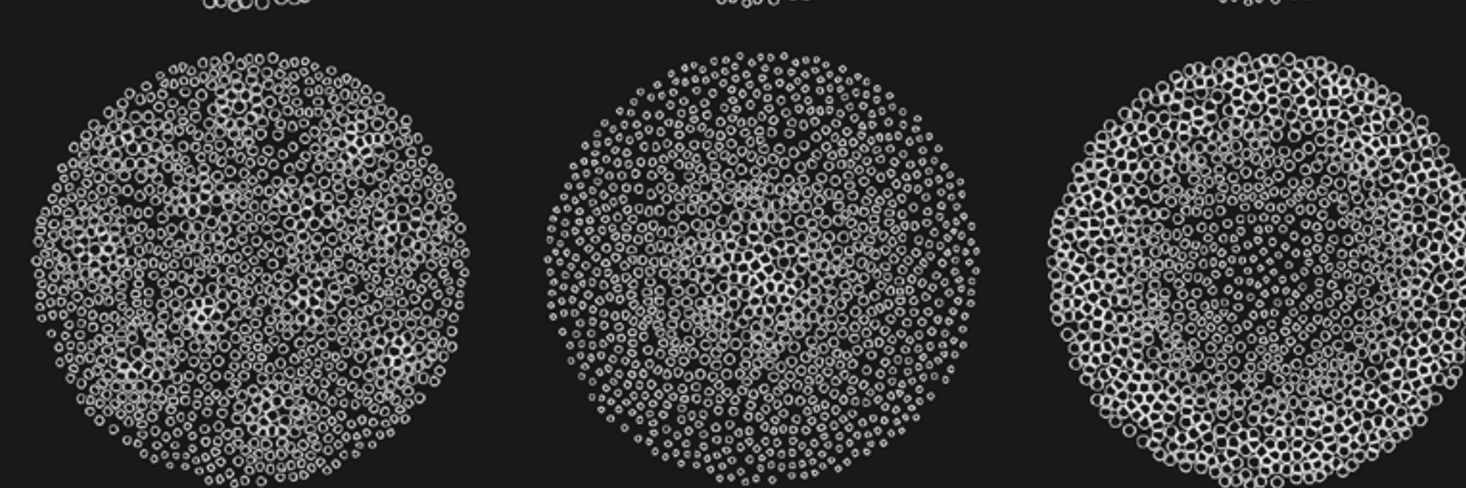



Figure [102]. Pattern variations

PROTOTYPING

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Pattern Imitation ALSEDA

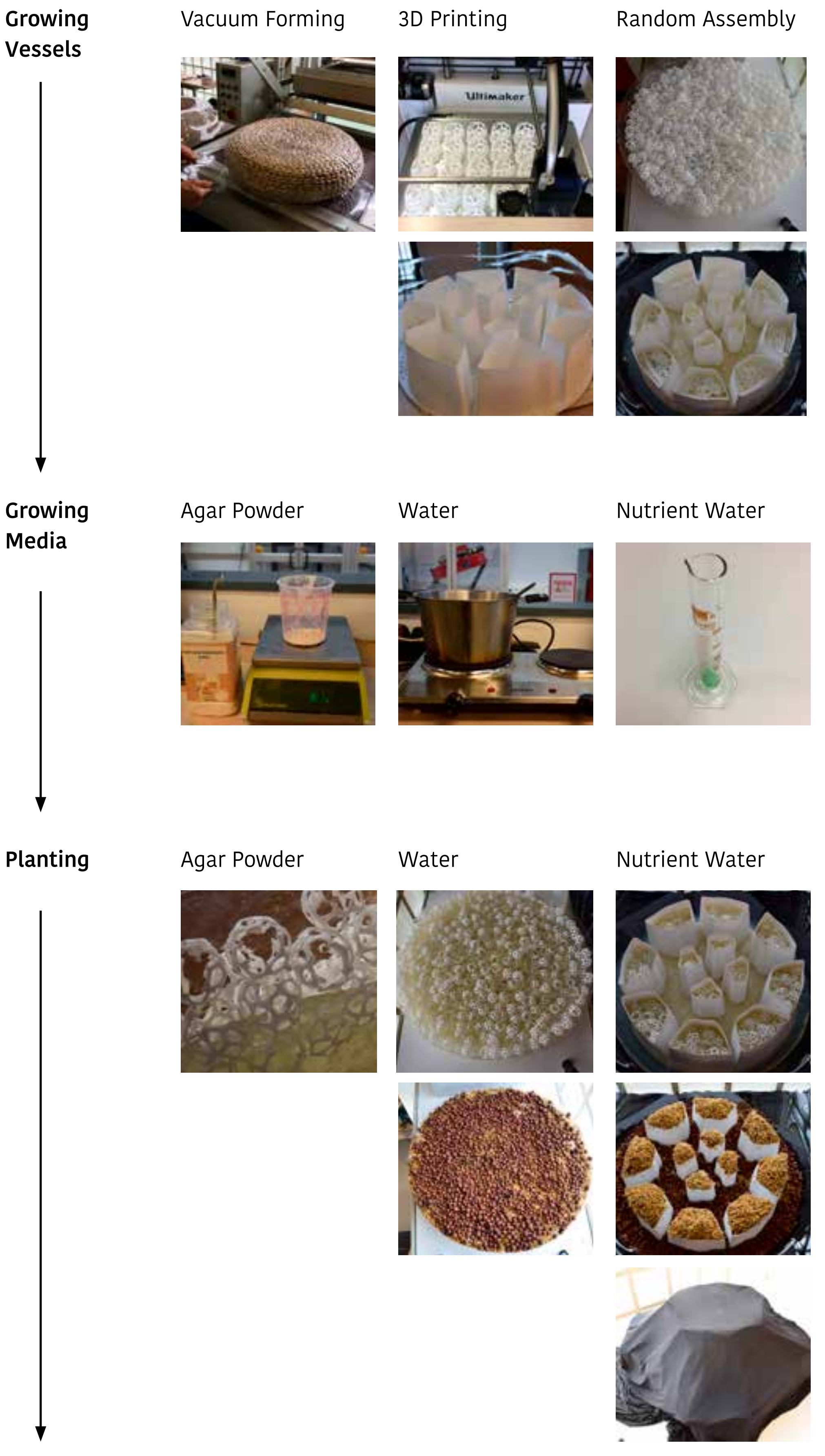
Two different techniques have been used to create an imitation pattern of the original IKEA ALSEDA. Both of them imitate the pattern to some extent: the first one show clear imitation in a distance, but not in detail; the second one is on a smaller scale due to limit of time and conditions, but it shows more in detail. The overall effect of the second is yet to know.

Figure [103]. Imitation test of ALSEDA pattern

Growing Optimized Form

A scaled down model (100mm *100mm* 100mm) of basic generated form has been created to test the principle of growing. If this form is seen as a table, then seeds are placed on top of the up-side-down legs. Some blue plastic particles are put in the legs, to see how roots interact with the obstacles on their way reaching the "table platform". It turned out that many roots have been prohibited by the particles, and not reaching the table platform. Reasons causing this might be complicatd and it is hard to draw a conclusion. However, for better results, seeds density could be higher and the total height could be lower.

Figure [104]. Experiment for optimized form testing



Model Size:
diameter 600 mm
height 160mm

Bead Number:
for imitation: 1200
for generative form: 300

Template Material:
for imitation model: PET
for generative model: PLA

Agar Powder:
8g / 1000ml water
supplier Natural Species Ltd.

Nutrient Water:
2.5ml / 1000ml water

Toal Water:
35L for imitation model
15L for generative model

Light Condition:
germinating: no light
ambient lighting, indoors

Germinating Time:
3-4 days

Growing Time:
5-7 days

Growing Process

Imitation Model

Shape Optimization Model

Harvesting after 1-2 Weeks

Drying

One half of the imitation model has been harvested. By the time of the report, the shape optimization model is still growing and therefore cannot be harvested. The photos of the imitation model will be shown in the next pages.

Half ALSEDA Remix
Imitation model
harvested on
16 Aug 2019 11 a.m.
wet & healthy

Diameter: 600mm
Height: 110mm

Details of ALSEDA Remix

8

Conclusion & Discussions

In this chapter, there will be a conclusion for the thesis, and discussions about the process, the material and the design. The evaluation of the research and design will be addressed and also limitations. Recommendations for future research and design will be made and personal reflections.

PROJECT CONCLUSION

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Interwoven is a textile grown from plant roots, showing the intelligence of plants. It is originally from the attempt of training plant roots to form a manmade pattern since 2015 by visual artist Diana Scherer based in Amsterdam. Due to fragility, it still remains an artistic work. However, Interwoven has a great potential for sustainable product design if further development is made through altering the material structure.

Collaborating with Materials Experience Lab of Industrial Design Engineering in TU Delft, Diana Scherer wants to bring an artistic material closer to people's daily life. This project followed the Material Driven Design method (Karana et al., 2015)*, has developed the material by altering material structure through hacking the growing process, incorporating generative design techniques.

Generative design techniques are used for shape optimization; parametric design techniques are used to design the structural pattern for achieving functionally graded material properties (e.g. spatially graded stiffness). Programmable material thinking has been explored to create a temporal material structure.

Based on Diana Scherer's experience and early experiments, a few techniques are synthesized and developed in the tinkering with Interwoven. Some potential structures for digital biofabrication: [1] root growth can be manipulated to mirror digitally generated patterns, which would provide intended technical and experiential characteristics in Interwoven; [2] roots grown in agar gel change properties to stiffer and stronger by hand feeling (further mechanical tests are needed), Interwoven becomes re-formable with water, into 3D forms; [3] roots can sew through descrete obstacles in their growing direction and these obstacles can be designed with digital fabrication techniques.

The ability to co-create structures have been further explored in this project. The results from the user studies, with a particular emphasis on how people interpret the material structure: alien, strange, confusion and conflict between nature and man-made world.
In order to materialise the experience vision, an experience vision study in the form of ideation has been done. The final product concept is to imitate one of the most mass-produced daily products - IKEA ALSEDA, questioning the current way of manufacturing and material use. It also creates an experience of the blend of nature and man-made world.

Digital manufacturing has been incorporated in the growing of a bio-material and create a meaningful combination with roots. The project acts as starting point for further research and design with Interwoven to be applied in people's daily life as an alternative material.

EVALUATION OF DESIGN

-

Based on the design vision established, the design should "exhibit the glue-ability of roots through a daily object co-created by roots and digital manufactured structures and bring forward the collision and collaboration between natural growth and man-made world." The evaluation lies in the prototyping process and results. Since the shape optimization model is still in growing process, the results are only seen from the imitation model for the moment. Further evaluation should be made when both models are ready.

Experience Vision

Exhibit the Glue-ability
The project emphasizes roots' ability to connect porous 3D printed PLA structure. The design is made with descrete 3D units. Roots serve as glue in the making process of the volumetric object. The goal is reached in terms of functionality of roots and show affordance of Interwoven as glue. It demonstrates Interwoven potential in creating 3D forms for daily object design and potential in enhaced strength.

Showing Traces of Organic Growth
Traces of organic growth has been carefully designed with abundant gradient experiments. Through microscopic examinations, the growing traces have been carefully analysed and then designed. The nuances between different size, depth and shape are well mapped out. Traces are reflected on the skin of the final design: either to imitate IKEA ALSEDA, or to show patterns to invite people to touch.

Using of Digital Fabrication
Different techniques of digital fabrication have been explored, such as 3D printing, parametric design, shape optimization, programmable materials. Although not all of them have been systematically applied to Interwoven, early experiments in the project could offer base for further research. The final concept incorporates digital fabrication by designing the inner structure using parametric design and 3D printing technique, and optimize the shape of designed product by using TopOpt3D.

Bringing Forward the Collision and Collaboration
By studying experience vision pattern, using Interwoven for a daily object could trigger people's curiosity in trying out the strength of such delicate looking material. Creating a transition between different material properties can also help to emphasize the blend of nature and man-made objects. The principles are used in the final design. The 3D printed structures should be shown more intentionally to increase the conflict.

Project Brief

Durability has been increased by increasing the overall strength of the material. Root strength itself has not been tackled or increased, but the co-creating structure with 3D printed porous units. The intervention is incorporated in the growing process without doing any 'harm' to root growth. The technique gives Interwoven possibility to form 3D volumetric forms which would lead to wider applications. Showing the material potential with IKEA ALSEDA Remix emphasizes the material's role in furniture design and everyday object design. Further research is needed to look for a suitable business model and end-life solution.

Limitations

Limited Depth
The limited depth of root growth decides the limited height of the final design. Within a week, roots could only grow with high quality to around 80 mm.

Technical Performace
Due to limitation of time, only one iteration of the co-creation composite has been conducted a technical test. The structure used in the final design hasn't been tested yet. The final prototype is actually a test sample, instead of a confident product. Further research is needed to perfect the design.

RECOMMENDATIONS

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Exploring Porous Structures

Porous structures should be further explored to enable more capabilities of the composite structure. For example, making the composite more flexible and even elastic.

Improving Production Method

Scaling Up
With the limited scale of 3D printing equipment in the faculty, the design is limited to a reletively manageable scale produced within a two weeks. However, with development of additive manufacturing, it is not hard to imagine a future object scaling up to architecture level.

Preventing Molds
Currently there are visible molds and spores around the seeds, which might increase doubt about safety of using the product. The molds are caused by exceeding humidity in the growing conditions and some other unknown reasons. Mold-proof chemicals could be used, and more sterile growing environment could be built.

Other Insights Incorporated

Other insights discovered in the tinkering process have equal values for further explorations. Due to limit of time and project scope, those insights have been set aside.

Playing with Agar
Agar as a growing media changes the root properties. Different ratios of agar to water should be investigated to see the best result in desired material properties. Agar has potential to be the material for making growing vessels as well. There are a lot of research about bio-plastics related to agar and its shrinkage, relevant to molding.

Rotational Model
The rotational model is still interesting to incorporate human interactions in the growing process. For instance, maybe sports activities could be incorporated to generate the rotating speed. Wind energy could also be utilised for rotating a scaled-up growing vessel.

Prolonging Growing Time

The current growing time of each batch is around 7 days. However, normal growing time for oats could be months. It should be further investigated if it is possible to grow oats until the next generation of seeds have been produced by themselves. In this way, real sustainability could be reached.

End Life Recycling

There is an opportunity to recycle the PLA structure inside roots. However within the limit of time, the possibility hasn't been explored yet. It is only known that PLA degrades after 6 months in normal natural compost, while roots degrade much faster.

REFLECTIONS

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Tinkering Plan

Explorative phase of tinkering could be shorter while more time should be put into focused tinkering. As a personal issure, usually exloring phase is more interesting. However, the porous obstacle design should have been delved into more deeply.

Prototyping

I have met a lot of difficulties in the final prototyping. Despite all the problems sorted, seeds are quite unpredictable, in terms of how well they germinate. The planting of the generative model was delayed for one day because I couldn't finish it in the previous day, which resulted in less germination rate of seeds. The agar gel level in the pillars should also be lower to allow shorter growing height. Because it will then be easier for roots to reach the bottom of the growing vessel. Patterns will be mirrored better.

In General

Designing with Interwoven is a enjoyful process. However, there are a lot of hard times. It is enjoyful because I could meet and observe something new every week and think about how this can be used in design. It is intriguing to learn about roots and their ability to become useful materials. This novelty also brought difficulties: very unpredictable and it takes very long to get along with growing in a more controllable manner.

Useful Suggestions

If you design with living organism, keep your mind open for the organism to take control of you. The process will be full of surprise, instead of frustrations. When the material doesn't do what you want, just let it be and dig out values in it.

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9

Appendix

This appendix includes all documents from material tinkering diary, with photos, process and reflections; material benchmarking; and focus group results for ideation.

APPENDIX A
TINKERING DIARY

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I-0
Roots Climb down Moistered Surface

Date: 05-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to see if the roots will grow to map a shell surface
2) to see if cotton pads will offer enough conditions for root growth
3) to observe some basics about root growth
Process:
1). Take a glass and put upside-down
2). place soaked cotton pads
3). put 17 soaked (12hours) and germinated seeds on the top
4). spray some water whean it gets dry

Observation:
1). surface gets dry really fast
2). only 6 out of 17 seeds survived
3). the roots look unhealthy at all
4). the shoots cannot self-support their weight after getting higher and higher
5). after 9 days, the top area dried out and the seeds died.

Takeaways:
1). there should be a way to keep moisture
2). seed density should increase so that they can support themselves.
3). cotton pads work and roots attach to them, they also go in and out.
4). roots stitch the cotton pads together, like threads

Roots stitch the cotton pads together. Single root is stronger before drying out. However, I could still 'catapult' a dry root.

I-1
First Trial piece of Diana's Method

Date: 08-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to have a first try of Diana's method
2) to test the growing conditions in the current work space
3) to observe root growing in a transparent container

Process:
1). drill 5 holes of 6mm underneath the transparent plastic container
2). Use Diana's method to plant seeds
3). the seeds are not soaked before
4). the number of seeds: a surfaceful of the container
5). water the mixture thoroughly
6). turn on the growing light
7). on the 4th day, add some water
8). on the 7th day, take it out of the container to breathe some fress air

Observation:
1). the next day, almost every seed start to sprout at the same time
2). on the 3rd day, each seed had 3 white extentions
3). on 12-04-2019, the seeds are starting to shoot
4). the surface of the soil got really dry on the 4th day, that's when I added some water, but not too much
5). on the 7th day, the grasses look healthy, roots grew to the bottom, and even leak out of template
6). outside the container, the roots on the edge got easily dried out soon

Takeaways:
1). the final piece is very fine and thin, because at least 3 times of seeds are needed for a robust result
2). the seeds don't need to be soaked before hand, if they are planted on substrate like coco coir.

Lines are deeper and thinner, creating a spongy reaction to compression.

TINKERING DIARY

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I-2
Roots Forming a Shell

Date: 10-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to see if roots can form a vertical pattern through filling up the paths
2) to test bio-glue influence on root growth

Process:
1). 3D print a growing vessel
2). sandwich seeds with layers of coco coir
3). the number of seeds: a surfaceful of the vessel
4) coat half of the vessel surface with skin adhesive (a bio-glue)
5) the seeds are pre-soaked and germinated to 2-5mm
6) give thoroughly water and put it under growing light
7) give some water 2 days later

Observation & action:
On 5th day, the surface got really dry, so I took out the seeds with roots and found only poorly a bunch roots were there, so I drenched the whole vessel into water, and added some coco coir on top. On the 6th day, the improvement was seen effective because the grasses were healthier and taller. Only one root at each void position.

Takeaways:
1). a bigger surface or more seeds are needed to observe obvious root behaviour pattern, a second iteration is needed
2). skin adhesive doesn't have prohibition effect on the root growth

Roots should be immersed in their food in order to survive in the void space. A few seeds don't show the pattern.



I-3,4
Rotate the Template Once in a While

Date: 10-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to rotate the template while roots are growing, see what will happen
2) to see if roots will wrap around the cylinder shape and form a 3D cylinder with pattern

Process:
1). 3D print a growing vessel, 2 half cube shells and a cylinder (with/without pattern), coat half of the vessel surface with skin adhesive (a bio-glue)
2). sandwich seeds with layers of coco coir
3). the number of seeds: a surfaceful of the vessel
5) the seeds are pre-soaked and germinated to 2-5mm
6) give thoroughly water and put it under growing light
7) give some water at the bottom 5 days later

Observation:
1). on 5th day, grasses were healthy
2). hard to rotate a the beginning, which means root stuck to the template, but when a bigger force was applied, rotation got easy

Takeaways:
1). the roots only grow downward, but not so much wrap around the cylinder at the bottom
2). rotating the template doesn't rotate the roots because they stuck to substrate

Roots don't wrap around along the cylinder but reach the bottom of the container. The template rotation will make roots slip out of the pattern.





TINKERING DIARY

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I-5
The Grow-Ability of Roots into Width & Depth

Date: 09-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to test the growability of roots: in what depth, width and shape can it grow and the morphology of each one
2) to explore a proper way of putting the template in the coco coir

Process:
1). prepare a template with different shapes, width and depth of void space
2). put it in a bigger container and cover with coco coir to the same height as the template
3). put grids and then coco coir
4). put in a surfaceful of seeds and cover with a loose layer of coco coir
5). add enough water
6). water in the centre area on the 9th day

Observation:
1). root length developed unevenly
2). root density is low
3). cannot observe the situation within the target area

Takeaways:
1). there should be much more seeds to ensure large density of roots
2). find a way to observe what's happening in the template
3). there should be nutrient in the template

Roots were unable to penetrate these layers of tissue paper to get into the template. On the contrary, they got to the bottom and searched for water and nutrients there.

I-6
Purely water enables prosperity while making roots lazy.

Date: 09-04-2019
Conditions: 20˚C, indoor lighting

Purpose:
1) the sifter is used to drain the pre-soaked seeds prepared for tests, no special purpose to test
2) it was unexpected to have observed root behaviour in pure water

Process:
1). pre-soake seeds for 12 hours
2). drain the seeds in darkness
3). rinse and drain every 12 hours
4). some leftover seeds were left on the sift, with a container at the bottom, for 2 days
5). there is some water in the container, the level is lower than the sifter

Observation:
1). shoots are starting and are very green
2). roots penetrate the bottom of the sifter and reached water
3). roots are parallel to each other
4). root hairs are dense, white and strongly linked with each other
5). roots look fresh and juicy

Takeaways:
1). this method can be used to take single roots for technical characterization
2). roots grown in pure water look fresh and clean, very good way to observe them
3). root hairs are only in the upper part

Root hairs bind roots together in the mature part. Roots don't search for nutrients in the water actively, instead they stay in the positive gratropism position.

TINKERING DIARY

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I-7
Roots Grow in-between Rocks in Nature.

Date: 17-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to test the grow-ability of roots in-between rocks
2) to test if roots develop faster by transplanting pre-grown seedlings

Process:
1). 3D modelling hexagons as above, 2 layers, slightly connected for easy disassembly
2). connect 2 layers with double tape and small gadgets
3). assembly the vessel and fill with some coco coir
4). transplant some seedlings on top, add water

Observation:
1). several hours later, the roots started to go downward
2). the leaves didn't look so healthy
3). finally the roots don't extend too much
4). the roots only went along vertical directions, not in-between layers

Takeaways:
1). tranplanting doesn't work for strong root
2). the rock model should be redesigned to create obstacles in vertical directions

Transplanted roots can still grow but in a very weak way. Roots will grow only downward if no obstacles met in their way ;)

I-8
Will roots fill up the void space on the wall of vase in water?

Date: 11-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to test if roots will fill up void space with vertical patterns on the vessel in water
Process:
1). create a silicone vase with a hole at the bottom
2). put it in a bigger container, fill the container with water till the level of seeds
3). put a layer of grids and then some tissue paper layers
Observation & Iteration:
1). couldn't observe the process
2). the roots didn't penetrate much through the grids and tissue paper, so I took off a half circle of the paper
3). water dried out so soon and it's hard to refill, the vase tended to float

Takeaways:
1). there shouldn't be a hole at the bottom
2). tissue paper should be thinner layer
3). there should be much more seeds
4). maybe water is not a good idea because roots didn't search and thus no pattern formed

Water cultivation doesn't facillitate roots forming patterns. Roots stay still in water.

TINKERING DIARY

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I-9
2.5D Volume
Observation in Growth

Date: 09-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) observe how roots going down to the water layer
2) to test if roots can form a 2.5D volume

Process:
1). 3D print this growing vessel
2). put tissue paper, seeds and some coco coir on the upper layer
3). put a mixture of coco coir and water in the lower layer, assembly them together

Observation:
1). no a single root went down to the lower layer
2). it's really hard to keep the lower layer wet because the water dried out so quickly
3). only a few seeds survived in the upper layer

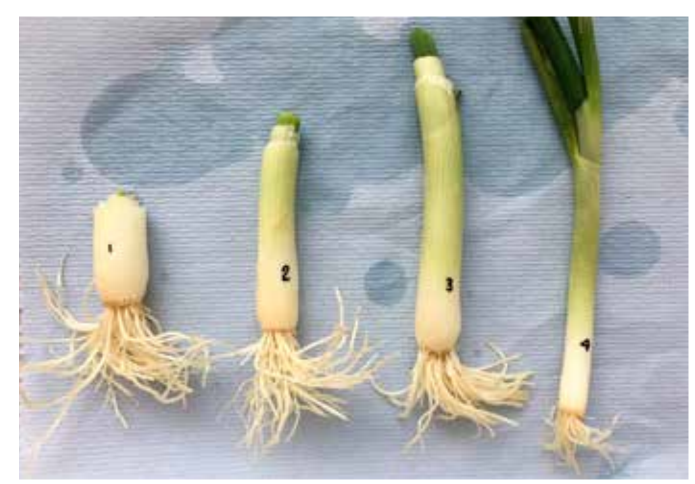
Takeaways:
The reasons for the failure of the sample could be:
1) there should be more seeds
2). the roots need moisture and darkness, some wrapping at the bottom can help
3). the roots cannot penetrate the tissue papers because they are too thick
4). the upper vesser should be deeper and coco coir should be more to create a better environment for seeds and roots

Roots like water and darkness. They don't like light, therefore in order to observe, there should be a wrapping to keep dark while able to take off when observing.

I-10
Green onion and chives seem to have very prosperous roots.

Date: 11-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test if grown chives and green onions can develop root length furthur and show same searching behaviour as oat grasses
Process:
1). cut 4 different lengths of green onions and replant them in water
2). replant some grown chives on a vessel with grids at the bottom, give water
Observation:
1). the lengths of roots do not increase in either green onion and chives.
2). they both generated new young roots
3). both of them don't have root hairs which bind the roots together
Takeaways:
The root hairs of oat is unique about it. Green onions and chives are not alternative.



The root hairs are unique in oat grass. Green onions and chives develop new roots but developed roots don't connect at all.

TINKERING DIARY

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Other interesting facts

Roots swirl in a volumetic void shape.

Roots like to gather at the bottom.

Roots leak to wherever there's space and water/nutrients.

Always 3 roots with a shoot

General Takeaways

Number of Seeds
According to Diana, the number of seeds should increase at least 3 times than the current number. Too few seeds will influence the results to a large degree due to either the ratio of germination in this season is low, or the number of roots are small.

Darkness
Roots grow in dark environment, so it is not wise to keep light in because I wanted to observe the growing process. Aluminium foil could be used to wrap the root area outside the container.

Water Cultivation
Deep water cultivation should be avoided because water pamper roots and they don't show searching pattern very well. Coco coir works well with seeds from the beginning of germination. However, shallow water cultivation is recommended by Diana, and other substrate like agar is still open for experimentation.

Nutritions
Although seedlings are young and vibrant, they need a little nutrients as stimulus for growing. Therefore, instead of water added in the beginning and on the 3rd day of growth, add nutrient water at the right solution ratio is essential.

Iteration
Rock model, rotation model and vertical pattern model are still interesting for a second round of experiments. Improvements should be made building upon insights got in Tinkering I.

TINKERING DIARY

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II-1, 2
Thin layer of water above template vs. Coco coir

Date: 24-04-2019
Conditions: 20˚C, growing led, 6am-8pm

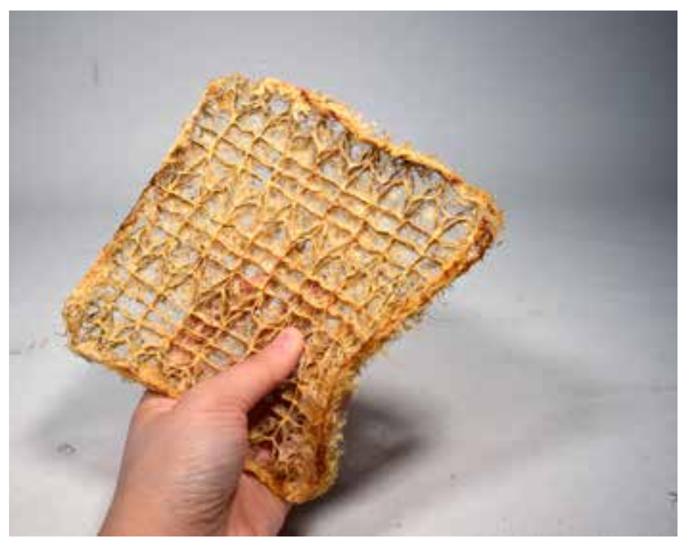
Purpose:
to compare the growing situation in coco coir and water conditions

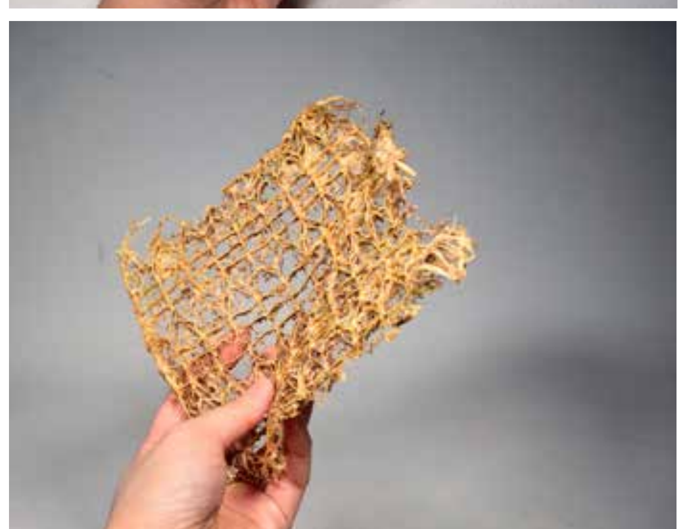
Process:
1). prepare 2 containers of the same size
2). in one container, use Diana's original method to plant, but with 3 cups (soup cup from Jumbo) of seeds; in another container, don't put any coco coir, but just nutrient water; cover the water sample with a thin piece of tissue paper
3). place under the growing light

Observation:
1). the water sample got dried out very fast, the surface almost dry and no seeds from the first layer started to germinate.
2). the bottom of the container always has some water, but looks not so fresh and clear
3). after 4 days, some hydragel were put on half of the surface of the water sample to keep moisture and see effects, but no obvious effect on the final results
4). both of these samples didn't show thriving and healthy grasses, while the roots are robust in the end, which might proove that drought increases root density.
5). the samples shrivel after drying.

Takeaways:
the water sample is more dense and strong than the coco-coir sample.

Thin layer water helps roots to densify. When drying, the material shrivels. The wrapping effect is interesting. They look burnt, when lacked in Oxygen.



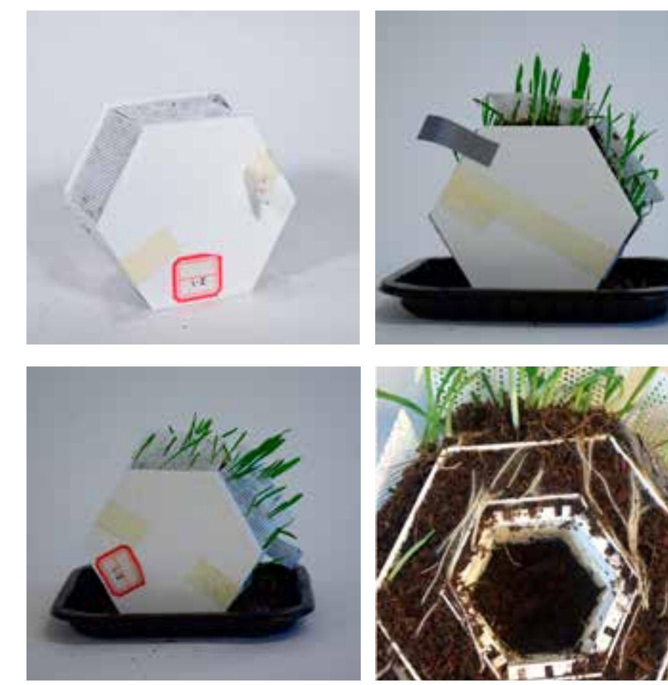


II-3
Iteration on the previous rotation model

Date: 24-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to test the root behaviour when rotated 60 degrees every 12 hours
2) to test if the roots can map on the hexagonal column
3) to test if seed paper works
Process:
1). make seed paper with recycled newspaper and seeds
2). damp the seed paper and paste on every facade of the hexagonal colume
3). fill the column with coco coir and add water
4). rotate every 12 hours
Observation:
1). the roots and shoots grew too fast. The roots already took shape of positive gravitropism before I was able to rotate
2). the shoots grew out from the outside layer of grids, which make it difficult to survive at the bottom.
3). 3rd and 4th days were weekends, when I was not able to rotate the model: one facade of seeds grew very tall, while other facades didn't grow at all and it was too late
Takeaways:
1) during the first 4 days of germination, rotation should be very even and fast, so no facade was dominent
2). while rotating, there should be space underneath for the grasses to fit, otherwise they will be compressed and stuck. They should still be able to see light.
3). seed paper works

Each single root will swirl when rotated every 12 hours. What if the rotation speed is so fast that it causes centrifugal force to the roots?



TINKERING DIARY

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II-4
Another iteration on the rotation model

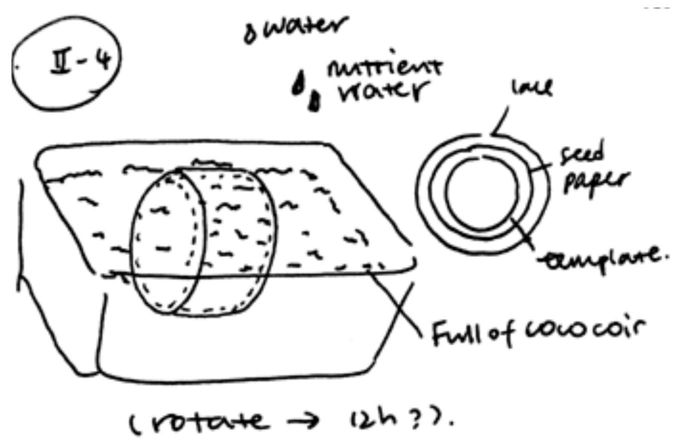
Date: 25-04-2019
Conditions: 20˚C, growing led, 6am-8pm

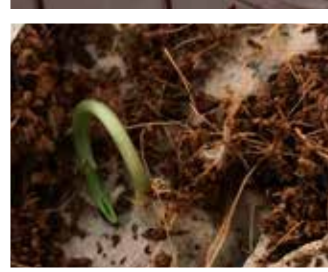
Purpose:
1) to test if roots can growth onto the pattern on the cylinder shape by rotating it in the coco coir
2) to compare this with II-3

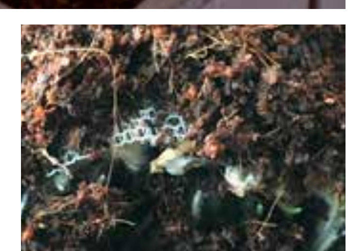
Process:
1). damp the seed paper and put it around the cylinder surface
2). put a layer of lace textile on the outside
3). put them in a bigger container, add coco coir and nutrient water
4). rotate every 12 hours

Observation:
1). during the weekeds, when rotation is not possible, the surface seeds grew too fast and the bottom roots grew too long
2). germination ratio is very low

Takeaways:
This kind of rotation model won't work in general because the roots will swirl on its own place as is explained in the model II-3. A new model with centrifugal force should be made, seeds should be inside the shell instead of on the surface.







When rotating speed is low, the roots grow long so fast that they will swirl in their own position. Centrifugal force could be utilized to manipulate positive gravitropism.

II-5
Vertical pattern in coco coir

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test if roots can show pattern on the inner surface of the vase in an vertical way in coco coir

Process:
1). put a gadget to block the hole on the bottom of the vase
2). Use Diana's method to plant a lor of seeds in the silicone vase
3). give nutrient water

Observation:
normal growth from the leaves

Takeaways:
1). the roots show obvious pattern, even if it's vertical direction
2). it is very hard to remove the coco coir from the roots. Maybe they can viewed as a whole material.
3). it takes about 2 days to dry.
4). the roots don't repel the silicon material. On the contrast, they grow beside it. It is also very easy to take out the inside content out because of the flexibility of the silicon.

The roots show crossing and interwoven pattern on the surface of the volume.

TINKERING DIARY

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II-6
Growability Testing: what shape can it take?

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
1) to test the depth, width and shape that roots can grow into

Process:
1) Use Diana's method to plant a lot of seeds (3 times more than the Tinkering I)
2) Only put coco coir in above the mould to make the roots more focused in this area
3) put it in a bigger container but to the edges
4) use aluminium foil to cover the fourth edge

Observation:
1). when the aluminium foil was opend, there are some bugs in the roots there, which means a bit rotten the roots are
2). there's also a rotten smell from the roots
3). roots on the edges grew to the bottom and even searched for a while at the bottom, but not so much growth in the template itself

Takeaways:
1). The air flow of the container should increase, although the burnt color is nice
2). the nutrients in the silicone mould is not enough for 7 days. Maybe agar is a good idea.

In rings, the roots go along the ring circle; in volumetric shapes, roots swirl; in deep and narrow shapes, roots go straight down.

II-7
Roots growing on other fabric

Date: 25-04-2019 Growing 7 days
Conditions: 20˚C, growing led, 6am-8pm

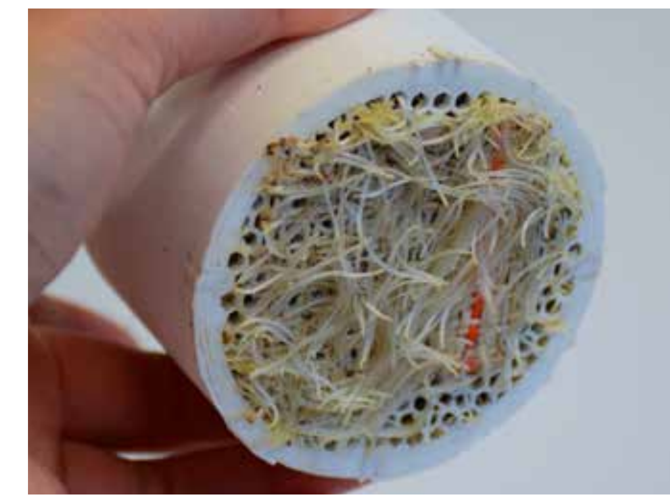
Purpose:
to test the combination with another fabric with woven structure; will roots interwine with it together? What will be pattern?

Process:
1). put coco coir and seeds in a 3D printed container, with grids as the bottom
2) put a damped woven fabric at the bottom

Observation:
1). roots grow across the fabric in a disordered way
2). the fabric is kept tightly to the container by roots
3). the moisture at the bottom of the container is enough for the roots to live a good life

Takeaways:
1). there should be a grid layer between the container and the fabric for cutting to harvest the fabric with roots; otherwise on the other side of the fabric, roots will be so short to be more stable and locked to the fabric.
2). the fabric definitely makes the whole strucuture stronger, but it doesn't show the pattern at the moment, which could be developed.

Roots can also be seen as adhesive to other materials.
The roots in its natural status on a platform is very disordered, showing individual's randomness.



TINKERING DIARY

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II-8
Redoing the vertical path model with coco coir

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

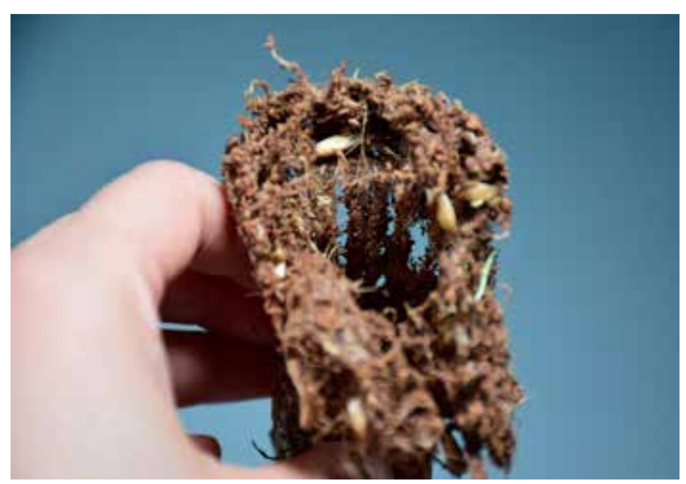
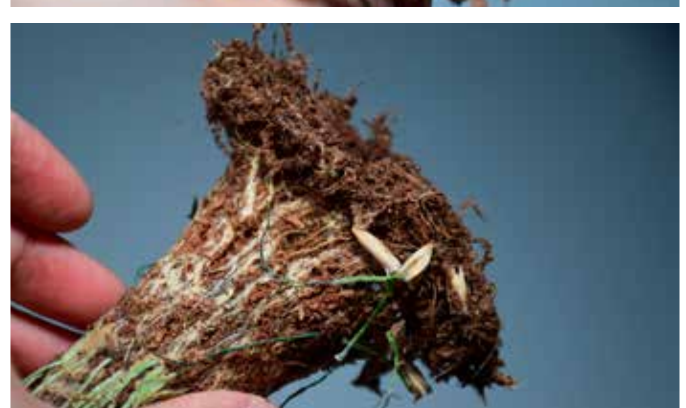
Purpose:
Re-try the vertical path model, but with coco coir instead of water; the number of seeds increase

Process:
1). put coco coir into the mould, fill it entirely
2). put a lot of seeds and then a thin layer of coco coir again at the top
3). add enough water
4). the seeds are not pre-soaked
5). put the whole model into a bigger container and add some moistured coco coir to the bottom of the container

Observation:
1). on 26th, the surface became very dry and then I wrap aluinium foil on the edge and added some more moistured coco coir
2). in the following days the seedlings looked quite healthy
3). the roots grew out of the model and into the coco coir in the bigger container
4). the results show that this time the roots are much denser. However the roots look very weak and not fresh

Takeaways:
1). there should be a way to remove the coco coir if it's necessary
2). the whole structure cannot stand on its own and the vertical pattern is very weak in general

In some part there is a weak sign of pattern, not appealing, though. The roots just don't search and strengthen themselves so much vertically.

II-14, 15, 21, 22
Immitating rocks in water, coco coir and agar

Date: II-14, 15 25-04-2019; II-21,22 28-04-2019 Growing Days: 7
Conditions:
II-14,15 20˚C, growing led, 6am-8pm
II-21,22 20˚C, half-shaded at home

Purpose:
iterate on the rock immitation model; to test if agar works in this model and to test taking out the 'rocks' after harvesting and drying; to test if randomness of the obstacles will create horizontal structure

Process:
1). put the 'rocks' in a container
2). put in the substrate: water, coco coir or agar
3). the seeds in the agar sample were pre-soaked overnight to have more moisture
4). cover the agar sample with aluminium foil with holes
5). cover the root part with aluminium foil in all the samples to provide darkness for them

Observation:
In all of the samples, roots grow very fast and look healthy. Especially in agar samples, roots show very fast growing even without the growing light.

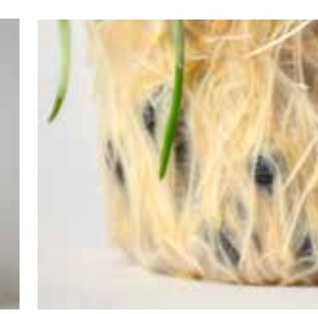
Takeaways:
1). agar is a very helping substrate for root growth

The roots embraced the 'rocks' entirely and it's impossible to take the rocks out.

Roots grown on agar take much longer to dry out and the texture is more gentle. It is very interesting that the roots have eaten the agar that they grew on.







TINKERING DIARY

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II-10
What if guiding roots growth and let them cross?

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test if roots can cross if their growing direction is guided by either gravity or direction of gradience of moisture
Process:
1). 3D print a container as above and fill it with coco coir
2). damp two small pieces of seed paper and paste them on the surface of the open area of the substrate
3). cover one side with grid and let the other side face upward first
Observation:
Only the side which face upward first shooted
Takeaways:
1). there shouldn't be too much shooting time difference of the two sides.

**Apparently, no roots cross because all roots will turn their head to the same direction whenever I rotate the vase.
They do show a sign of turning.**

II-11
Iteration on the 2.5D form test

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to try the 2.5D model again with modified technique

Process:
1). fill the lower par with nutrient water
2). put seeds and coco coir on the upper layer
3). wrap them with aluminium foil
4). put them in a bigger container
5). add more water into the aluminium structure

Observation:
1). the roots and shoots both grew very healthily
2). it is possible to observe the middle part but not possible to observe the pattern in the lower part
3). the roots are swirling in the void space in the lower part of the vessel
4). roots look very different when it's wet and dry: when they are wet, they look very dynamic and fresh, when dry, they look dead to me

Takeaways:
1). the aluminium foil is a good technique to keep moisture and darkness at the same time. It's good that the roots don't repel it.
2). the roots can grow in pure water and form a pattern but just with a thin layer of water
3). the 2.5D pattern is obvious because the pattern has some depth and bouncing effect when played in hand

**With this form, it looks very vibrant and dynamic when the roots are wet, but looks dead when roots dried out.
Flexible 2.5D forms creates a certain interactivity.**

TINKERING DIARY

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II-12
Will the pattern show distribution of density of roots?

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test if uneven distribution of seed density will cause the root pattern to show this distribution

Process:
Use Diana's original method to plant but distribution seeds very unevenly in the substrate

Observation:
The leaves were growing really well: steady and green. The pattern is not very obviously showing the distribution. Only that with the least dense seed area, there's almost no pattern. The overall density of the sample is low and the roots were not strong.

Takeaways:
The leaves grew well probably because there's more space for individuals. The roots don't show the distribution obviously, probably because the roots can find their way in the bottom area freely. The sample deformed and shriveled a lot because of drying out not on the grids.

Seed density influence the pattern density but not very regularly shown on the pattern.

II-13
Roots growing on roots

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test if new roots will interweave into old samples and how they interweave

Process:
1). to prevent rotting, drill 4 holes on the bottom of the container
2). place a previous dried sample to the bottom
3). place grids, seeds and coco coir
4). add nutrient water (5ml: 1L)

Observation:
Nothing special during the growing process. Nothing could be observed because the container is black.

I couldn't tell which is new and old roots on the harvested sample. They look very randomly interwoven and the pattern in the old sample was invisible.

Takeaways:
The structure becomes more complex, however it loses the pattern and become very random. Maybe there's a way to create a composite pattern by using a new pattern for the new roots while keep the old pattern of the old roots.

The composite structure is stronger but loses the pattern.

TINKERING DIARY

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II-16
Other plant type:
CORN

Date: 26-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to compare oat grass roots with corn roots in a casual way

Process:
sow some corn seeds in a transparent container

Observation:
1). the roots are around 1mm thick
2). the roots have some pink part close to the seeds
3). the rootts grow into the pattern of the container clearly but not so densely
4). they do have root hair as oat roots

Takeaways:
1). More research needed for knowing the grow-ability of corn roots into different forms.
2). As is told by Diana, corn roots are less obedient than oat roots although they are stronger. Considering 3D form objects or bigger object, corn roots are still a good option to consider.

Nicely pink-tinted roots with also root hairs. The roots are much stronger and bigger. They are also less obient.

II-19
How are bean roots different from oat?

Date: 26-04-2019
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to compare oat grass roots with bean roots in a casual way

Process:
sow some mung bean seeds in a container

Observation:
1). the seeds germinated slowlier than oat but faster than corns
2). the roots are about the same thickness as oat roots
3). the roots show interesting circling pattern at the bottom of the pot
4). they don't look very fresh and dynamic as oat roots and don't show clearly root hairs

Takeaways:
1). More research needed for knowing the grow-ability of mung bean roots into different forms.
2). the growing pattern of the circling is intereting. There can be a comparison experiment with oat roots if necessary.

Very nicely and obviously showing a circling pattern at the bottom, which was not shown on oat grasses.

TINKERING DIARY

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II-17,18
Growing into a 3D form and pattern on surface

Date: 25-04-2019 Growing Days: 7
Conditions: 20˚C, growing led, 6am-8pm

Purpose:
to test growing roots into a 3D form: a vase given by Diana Scherer. The vase has pattern in the inner side.

Process:
1). 3D print the form mould, with pattern
2). brush the inside with epoxy, to smoothen the surface
3). put in coco coir and seeds, using Diana's method
4). place the half vase under the growing light
5). to compare seed density, one vase was filled with a lot of seeds, the other with less density of seeds

Observation:
1). It turned out that with less density of seeds, the grasses were more green and healthy, probably because they had more nutrient individually and more space to grow.
2). it was easy to harvest and the roots didn't get stuck in the pattern on the vase
3). on the bottom of the half vase, where there's an area with the deposit of the epoxy resin, the roots grew randomly and evenly into a flat piece
4). it was obvious that roots gathered more at the bottom of the form, instead of other positions, which prove again that they grow really towards the gravity

Takeaways:
1). depending on the growing space and capability of nutrients, there should be a balance of seed density. Not the denser, the better
2). It is almost impossible to remove the coco coir in the sample to get pure roots. To make use of this way of growing, I can try to use agar as substrate, since the roots will eat the agar and leave no other material in the end.

3). Now the vase is divided into two halves, to grow a entire piece, it is possible to spin the closed vase on a spinning machine

Obviously the maximum density is found at the bottom still. The volume is steady and strong, but with coco coir, supporting a lot.

II-20
How will roots behave on a slope? Will they form pattern?

Date: 26-04-2019 Growing Days: 12
Conditions: 20˚C, growing led, 6am-8pm

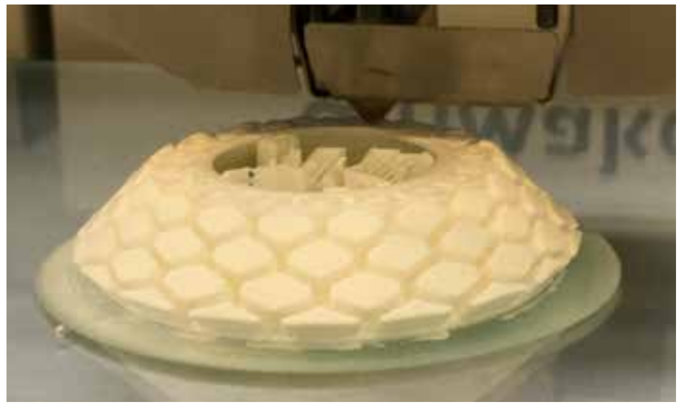
Purpose:
to test if roots can form a pattern and also a cone shape on template of 45˚ slope

Process:
1). 3D print a cone form, with pattern on the top
2). coat it with skin adhesive (a bio-glue)
3). wait 3 hours and place it at the bottom of a container
4). add coco coir and seeds
5). add nutrient water, and some hydrogel on the surface

Observation:
The roots didn't grow very well. They are not fresh and strong. It was hard to separate the cone with the other part: some roots were broken in order to do that. No obvious pattern or shape fomed.

Takeaways:
1). According to Diana, it could be that the coco coir was too much, the space was too much as well so the roots have other space to go into.
2). I should try another time with agar as substrate in a smaller container.

The reasons for a poor growth can vary a lot and it's hard to decide. The best thing to find out is to try again in a more proper condition for plant growth. In theory, this should work.



TINKERING DIARY

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II-23
Agar as Growing Media

Date: 26-04-2019 Growing Days: 7
Conditions: 20˚C, at home

Purpose:
To compare with the rock models and see what will happen if roots just grow un-directed in agar substrate

Process:
1). boil agar in nutrient water (2.5ml:1L)
2). sterilize a glass jar with alcohol and cool down agar solution in it
3). put 3cm thick seeds on the agar gel
4). cover the lid but leave some space for air flow

Observation:
1). when there' s nothing to obstacle roots, they go straight ahead to the bottom
2). the roots look clean, fresh and healthy in agar
3). the development of seeds are quite uneven, some shoot really early
4). the roots dry very slowly and texture is smoothe

Takeaways:
Agar is really potential for further experiments because of its cleaness, texture, nutrition and observability.

Roots have eaten almost all the agar that they fed on. Some roots connect to each other, some float in the air. A natural indent is seen, due to larger density at the bottom.

II-24
What if only a thin layer of Agar on template?

Date: 28-04-2019
Conditions: 20˚C, at home

Purpose:
to test roots growing on a thin layer of agar covering the template

Process:
1). boil agar in nutrient water (2.5ml:1L)
2). sterilize a plastic container with alcohol
3). put in the template and pour agar solution to cover it a little bit
3). put 3cm thick seeds on the cooled down agar gel
4). cover the lid but leave some space for air flow
5). cover the root part with aluminium foil to keep dark

Observation:
1). There is no need to water during the growth.
2). The grasses grew very healthily and tall.
3). They eat all the agar but left a very thin layer on the template and at the bottom of the template, which looks like bio-plastic.

Takeaways:
To dry the sample, I need to put the sample under the heater, and for 4 days it is still not yet completely dry. This drying process is very interesting to investigate, because it takes time and the material is always changing its properties. The thin layer of bio-plastic like material of the left agar shrivels a lot and becomes more brittle during the process.

The bio-plastic layer of the left-over agar change the texture of roots completely. The slow drying process creates a chronomaterial.

TINKERING DIARY

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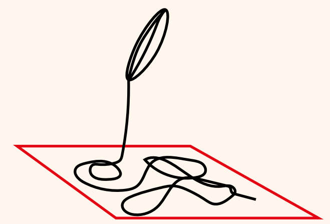
General Takeaways

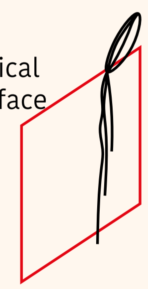
Dynamic Movement
Roots show positive gratropism, but also subjective to other external force like centrifugal force. Roots react to force input of humans.



Horizontal Surface

Power of Growing,
Embracing and Link to Nature
Immitating roots growing in rocks in nature, structure can be created showing the power of roots searching behaviour. They are embracing whatever is in their way towards water and nutrients

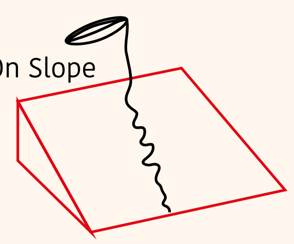
On Vertical Surface



3Dimensional
Growing 3D forms is still challenging in terms of pure root material. There's possibility to combine a 3D form with the spinning model.

physical Interaction
Modular forms (patterns) give affordance to physical interactivity.

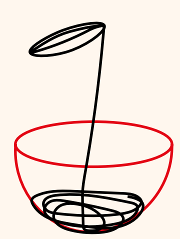
On Slope



Chronomaterial
Grown in agar as substrate, the material show time-related changes. It can be seen as chronomaterial.

Clean, fresh and young
Roots grown in agar are more fresh and clean.

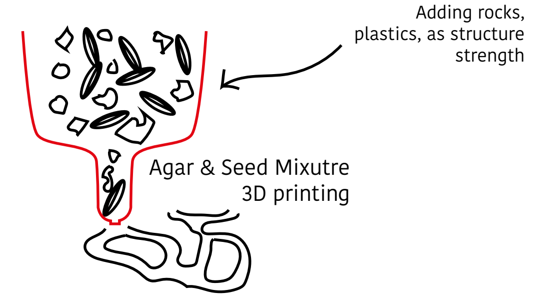
Leaking, penetrating
Roots ability to leak from wherever there's a hole, or to stitching whatever they can penetrate through show their powerfulness again.



In a Volume Space

In general, roots are dynamic and strong, not in the form of the final material, but in the process of their growth- in the traces of growth.

III-1, 2
[3D Print] Roots with Agar Mixture



Date: 12-05-2019
Conditions: Room Temperature 20˚C, Room light, half shade
Growing Time: 7 days

Purpose:
to explore 3D printing of a mixture of seeds and agar, compare 2 methods

Process:
1). make agar gel and cool it down
2). grind the agar gel
3). mix agar gel granules with pre-germinated seeds
4). put the mixture into a pastry bag and use decorating mouth to extrude them along a certain path on the bottom of a container.
4). in another container, only extrude agar gel in a path and them put seeds onto it, covering the whole surface.

Observation:
1). the seeds grow normally
2). the roots of the first method grow only in the area where there is agar gel, while the roots of the second method go everywhere

Takeaways:
1). the extrusion of the mixture is very hard because the granules are very large
2). the roots don't follow the path in the second method
3). in general, this way of manipulation of the structure is very hard to digitallize and control since the seeds are large and the mixture is very watery.

Roots follow the agar gel places but no exciting pattern or interesting behaviour is observed. Very hard to control the process as well.

TINKERING DIARY

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III-3
Growing Roots into a Shell form in Agar

Date: 12-05-2019
Conditions: Room Temperature 20˚C, Room light, half shade
Growing Time: 7 days

Purpose:
1) to test again the root growability on a slope shell with pattern
2) to test if roots form this pattern better in agar than in coco coir

Process:
1). prepare a sterilised glass container
2). make some agar gel
3). put the 3D printed template into the container, make sure the bottom is level
4). add some nutrient solution (2.5 : 500) into the agar solution before cooling down
5). pour in the agar solution and cool it down
6). cover a piece of tissue paper on the cone
7). put seeds onto the top

Observation:
1). the seeds grow normally
2). roots grow into the bottom of the cone and embrace the cone
3). there is a slight piece of agar plastic on the roots at the bottom
4). it's very hard to take the roots out of the template because the direction of the void space is normal to the surface instead of upward.

The pattern is recognizable but there should be a better way to demolding the roots since taking out messed up the pattern.

Takeaways:
1). the direction of the void space should face upward for an easy taking out of the roots
2). it's impossible to separate the mix and the roots themselves, so there should be grids inbetween
3). the void space on the cone is too small

III-4
the Grow-Ability of Roots in Agar Gel

Date: 12-05-2019
Conditions: Room Temperature 20˚C, Room light, half shade
Growing Time: 7 days

Purpose:
to test the grow-ability of roots in agar: how wide and how deep they can go

Process:
1). sterilise the container and the template
2). boil and make some agar gel and add nutrient solution (2.5:500 ml)
3). pour the hot mixture into the container, covering the void space in the template
4). put onto the surface seeds (3cm thick)

Observation:
1). seeds grow normally
2). there's a strong layer of bio-plastic formed with agar at the bottom, embedding the roots
3). the roots can show depth better than width; they didn't fill up the width of the void space but grow longer than the depth

Takeaways:
1). there should be a way to keep moisture
2). seed density should increase so that they can support themselves.
3). cotton pads work and roots attach to them, they also go in and out.
4). roots stitch the cotton pads together, like threads

Roots want to go deeper than wider

TINKERING DIARY

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III-5
Reaction to Water

Date: 14-05-2019
Conditions: 20˚C, soak with water until all wet

Purpose:
to see if the material is waterproof, and to test what will happen when it's soaked in water

Process:
1). soak the small piece of material with the agar plastic layer until it's completely wet
2). dry it, wrapping it around a small nail

Observation:
1). the piece of material becomes very soft and ductile after soaking
2). it is very easy to wrap in around the nail
3). it keeps the shape when drying
4). after drying, the material stays the shape and is hardened and stiff again

In order to know if the soaking washes away some stuff from the material, another two rounds of tests are conducted and the weight of the material is recorded:
1). 0.04213
2). 0.04157
3). 0.04049

Takeaways:
1). repeatable soaking is possible, but there's a slight weight loss
2). the technical characters of the sample need to be tested

The composite with agar plastic layer is interesting when the reaction to water is utilized in the final concept.

III-6
Sort of 2.5D Thick Piece with Pattern

Date: 14-05-2019
Conditions: Room Temperature 20˚C, Room light, half shade
Growing Time: 7 days

Purpose:
to test if a thick piece of 2.5D form with pattern can be formed in the growing media of agar gel

Process:
1). sterilise a container and the template
2). put the template in the bottom of the container, put in the grid with 4 feet to support a distance upper the template
3). boil agar solution and pour into the container
4). cool down the agar and put onto the surface seeds (3cm thick)

Observation:
1). the roots went to the bottom and wrap the template, need to be cut open
2). there's agar plastic layer at the bottom
3). some of the hexagons haven't been filled
4). when wet, the shape is very regular but when dry, the shape deforms, limseed oil doesn't improve the stability
5). the left part on the grids kept its shape well

Takeaways:
should let it dry in template to keep the shape

Agar gel as growing media ensures 3D space filled up with roots, and also stronger binding (by hand feel).

TINKERING DIARY

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III-7
Let the Roots Spin
Centrifugal Force

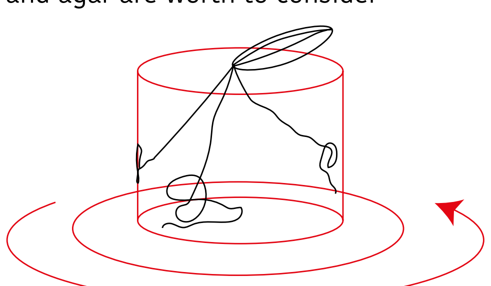
Date: 16-05-2019
Conditions: ~20˚C, indoor lighting
Growing Time: 11 days

Purpose:
to test the influence of centrifugal force on root growing direction; hypothesis: roots will grow more sideways than down

Process:
1). build a rotation model, making sure that the rotation speed is more than 3 times per second
2) fill the vase with agar and seeds as usual and seal the 2 halves together
3) keep the model on day and night (although I struggled with this for a long time and the total rotation time is about 36 hours I estimated)

Observation:
1) the roots fill up all the pattern space
2) there are molds at the bottom of shoots
3) a lot of agar are still left there

Takeaways:
1) the rotation should always be on for a more verified effect of centrifugal force
2) the agar gel is obviously too much, a mixtur e of seeds and agar are worth to consider



Electricity power is used, though. It might not fit in the philosophy of Interwoven, is it?

III-10
Roots Connecting Modulars - Wood

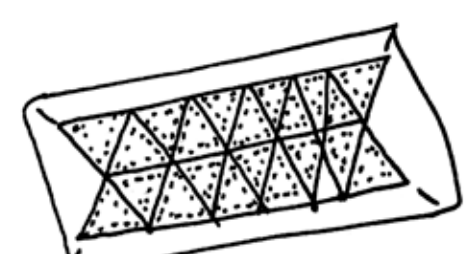
Date: 23-05-2019
Conditions: ~20˚C, natural light, half-shade for 4 days, growing led, 6am-8pm later

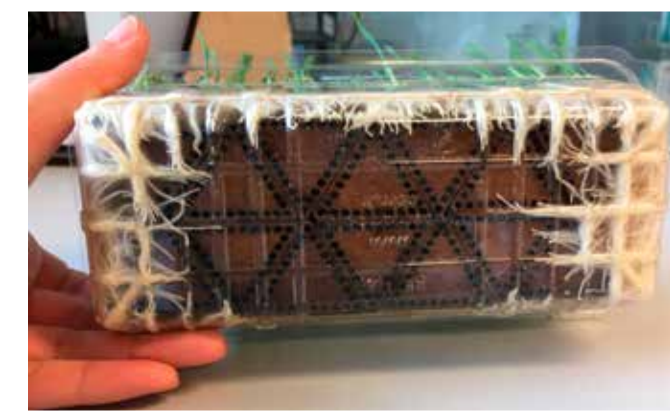
Purpose:
to test if roots can connect pieces of wood like issey miyake's textile

Process:
1). laser-cut wood pieces in triangles with arrays of holes on each side
2). put the pieces one to one at the bottom of a container and fold aluminium foil around it
3). boil some agar solution and pour into the template until it just covers the template
4). cool down the gel and put 2 pieces of grids
5) pour more agar solution onto the surface to cover the grids
6) cool down and put pre-germinated seeds on top when the agar gel is cooled down (seeds ~ 3cm thick)
7). cover with aluminium foil with holes

Observation:
1). The roots go down to the bottom along the side of the container instead of through the holes in the wood

Takeaways:
1) the wood might be not smooth enough
2) the carbon left on the wood might resist the roots





TINKERING DIARY

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III-11
Pattern on Vertical Surface in Agar

Date: 23-05-2019
Conditions: ~20˚C, natural light, half-shade for 4 days, growing led, 6am-8pm later

Purpose:
to test if roots can grow well in agar into a vertical surface with patterns

Process:
1). put the cylinder with pattern on the outside in a container
2). boil some agar solution and add some nutrient solution(2.5 : 500) to it
3). pour the agar solution into the container, covering the template
4). cool down the gel and put 2 pieces of grids
5) cover with aluminium foil with holes

Observation:
1). The roots grow really fast both inside and out side the cylinder; the pattern is not observable

Takeaways:
1) Roots don't take vertical patterns.
2) Roots form a natural waist shape in a big cylinder.

III-12
Roots Grown into Paper Structure

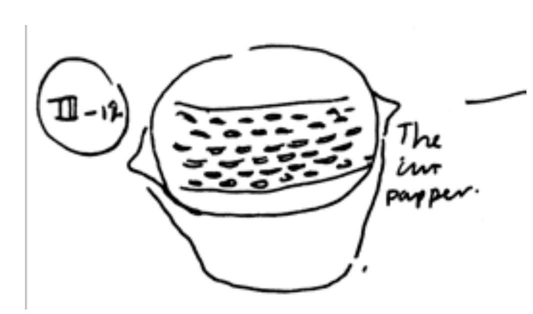
Date: 23-05-2019
Conditions: ~20˚C, natural light, half-shade for 4 days, growing led, 6am-8pm later

Purpose:
to test if roots grow through porous paper

Process:
1). cut a paper with the structure above
2). put the piece of paper at the bottom of a container
3). boil some agar solution and pour into the template until it just covers the paper
4). cool down the gel and put 2 pieces of grids
5) pour more agar solution onto the surface to cover the grids
6) cool down and put pre-germinated seeds on top when the agar gel is cooled down (seeds ~ 3cm thick)
7). cover with aluminium foil with holes

Observation:
The roots grow very well, much better than the wood sample III-10

Takeaway:
Roots grow through the paper totally, not only because it has holes.



APPENDIX B BENCHMARKING MANIPULATING NATURE

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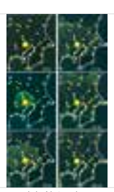
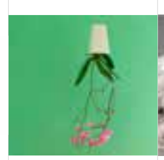
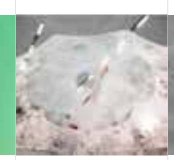
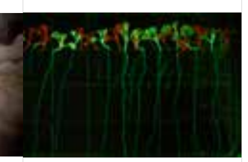
Manipulating Nature

Applications:
chair, light shade, network system, shop decoration, showcase of techniques, vase, billboard prints, bridge, architecture building bricks, packaging
Activities:
decoration, observing and learning, exhibiting, showing information, supporting, containing, weight bearing

Technical properties:
strong, ergonomic, stiff, compostable, heterogeneous
Experiential properties:
thought-provoking, sculptural, organic, slow, natural, delicate, careful, captive, changing with time, amazing, ingenious, natural, collaboration between human and nature, comparable to foam, light weight
Purpose:
making a sustainable way of growing furniture open-source, combination of biological and digital fabrication

Application Picture/ Sample						 								
name	Full Grown	Research in Network Formation in Physarum Polycephalum	Square Watermelon	Sky Planter	Silk Pavilion	Living Architecture	Continuous Bodies – Bodies of Change	ZERO Gravity	The Honey Comb Vase	Symbiosis	Living Root Bridges (locally known as jing kieng jri)	Water Based Digital Fabrication	Mycotree	
manufacturer	Full Grown Ltd.	Researchers: A. Tero, S. Takagi, T. Saigusa, K. Ito, D. P. Bebber, M. D. Fricker, K. Yumiki, R. Kobayashi, T. Nakagaki.	Yamashita family farm in Zentsuji city in Japan	Boskke Ltd.	MIT Media Lab	David Benjamin and his firm The Living	Officina Corpuscoli (Maurizio Montalti)	NASA	Studio Libertiny	Jelte van Abbema	local people, the Khasi Tribe in the mountainous plateau between Assam and Bangladesh	MIT Mediated Matter Group	Mycotech	Material science company Ecovative
composition	Willow/oak	Slime mold	Raw watermelon	Plant, Soil, filter grid, pot(ceramic and recycled)	Silk Worm silk, CNC silk fibres	Genetic modified bacteria, their growth by-product	Shroud inoculated with mycelia	Arabidopsis seeds	honeycomb, layer by layer made by bees	Bacteria printed on paper	aerial roots of the trees at the banks	Chitin, water Living matter in the form of cyanobacteria is coated and impregnated onto chitosan samples to enable surface functionalization and impart additional properties such as water resistance and conductivity.	Mycelium composite with wooden node	Mycelium with seed husk and corn stalks
technical properties	ergonomical, fastened in one solid piece stiff, durable	most efficient routes to get food for living	square, raw inside	-	a single continuous thread across patches providing various degrees of density.	generated flat sheets of material with distinct rigid and flexible regions; novel properties of structure and transparency	-	"...a number of genes involved in making and remodeling cell walls are expressed differently in space-grown plants. Other genes involved with light-sensing – normally expressed in leaves on Earth – are expressed in roots on the ISS. In leaves, many genes associated with plant hormone signaling are repressed, and genes associated with insect defense are more active."	ductile, soft	-	10-15 years of collaboration of human and nature to form; durable 500 years; bearing 500 people; flexible; growing stronger with rain and time	4D process	Weak in tension and bending but strong in compression; self-supporting; stable	Fully compostable, strong
experiential qualities	Natural, crafted, carbon-absorbing	inspiring	rare, expensive, eye-catching	upside-down; space saving	delicate but strong; combination of digital and biological fabrication	sophisticated; natural pattern	thought provoking	-	made by bees; sculptural; organic; slow	natural, delicate, careful, captive, changing with time	amazing, ingenious, natural, collaboration between human and nature	-	-	Comparable to foam, light weight,
applications	chair, lighting, table	a starting point for improving efficiency and decreasing costs for self-organized networks without centralized control, like remote sensor arrays, mobile ad hoc networks, and wireless mesh networks	at the beginning for saving space in transportation and storage, but as normal fruit the price was too high that no ordinary person want to buy; then it became just decoration for stores to show off	home/office plant decoration	a showcase of the relationship between digital and biological fabrication on product and architectural scales	new high-performance envelopes in buildings, boats and aeroplanes	shroud	gsrowing plants in low-gravity or no-gravity environment	vase	billboard prints	bridge	recyclable products or temporary architectural components such as tents	architectual level	wine bottle package
activities	decoration, function	-	show off; attract attention	decoration	exhibiting	exhibiting	exhibiting, showcase		containing flowers	changing with time; showing information; publicly captive	weight bearing		supporting	containing, protection
ultimate purpose	making the method open source (from the ted talk)	-	-	encouraging abundant greenery using a special reservoir that gradually feeds water to the plant' s roots, protecting against evaporation and drainage. The upside-down design also frees up floor space.	digital and biological fabrication on product and architectural scales	coporating bacteria and fungi into pattern design	explore and demistify the feelings of denial and anxiety, related to the acceptance of the loss of a beloved one, by transporting the process of decomposition of human remains to a more natural level, through an ecological, cyclical re-connection with our changing environment	explore space plant possibilities	to contradict the current consumer society; The process, which the designer calls "slow prototyping" in an ironic counterpoint to today's rapid manufacturing technologies	an alternative for media prints which put pressure on environment	connection between banks	recyclable products or temporary architectural components such as tents	to replace a lot of two-storay structures	to provide a natural alternative to traditional plastics and synthetic packaging
Process	the process starts by training and pruning young tree branches as they grow over specially made formers. At certain points the branches are grafted together so that the object grows in to one solid piece. After it's grown into the expected shape, people continue to care for and nurture the tree, while it thickens and matures, before harvesting it in the Winter and then letting it season and dry.	distribute food for slime mold on the spots of the map, place the slime mold and let it grow	adding a transparent cubic container to young watermelon and harvet before it ripens	hang the plant upside-down	the overall geometry of the pavilion was created using an algorithm that assigns a single continuous thread across patches providing various degrees of density. Overall density variation was informed by the silkworm itself deployed as a biological printer in the creation of a secondary structure. A swarm of 6,500 silkworms was positioned at the bottom rim of the scaffold spinning flat non-woven silk patches as they locally reinforced the gaps across CNC-deposited silk fibers.	two different types of genetically modified bacteria are mixed in a large petri dish with nutrients, and through their growth and interaction they generate flat sheets of material with distinct rigid and flexible regions.	inoculate a shroud with mycelium	a typical experiment begins on Earth in our lab with the planting of dormant Arabidopsis seeds in Petri plates containing a nutrient gel. This gel (unlike soil) stays put in zero gravity, and provides the water and nutrients the growing plants will need. The plates are then wrapped in dark cloth, taken to Kennedy Space Center, and eventually loaded into the Dragon Capsule on top of a Falcon 9 rocket to catch a ride to the ISS.	libertíny constructed vase-shaped beehive scaffolds (removed at the end of the process) and then let nature take its course: a group of bees went to work building a hive, layer by layer, in the same shape as the scaffold. The work took from two to ten days, depending on the weather, the season, the size of the colony, and its need to expand. It took one week and approximately forty thousand bees to complete this particular Honeycomb Vase.	printing composed bacteria text on the paper and create correct humidity and warmth to let them grow	local people building the bridge with the flexible aerial roots of the trees on the banks little by little, using stones and mud to make the walking path	the technology includes a robotically controlled AM system to produce biodegradable composite objects, combining natural hydrogels with other organic aggregates.	growing each single component in mould and connect them together with bamboo panel in a designed structure that keeps every component together in compression	about five days to grow around molds in a pre-determined packaging shape. In the process, mushroom fungi are killed and dehydrated, which takes away its ability to make more mushrooms

APPENDIX B BENCHMARKING ENHANCING NATURAL MATERIAL

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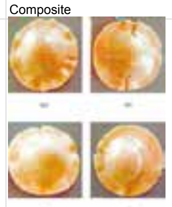
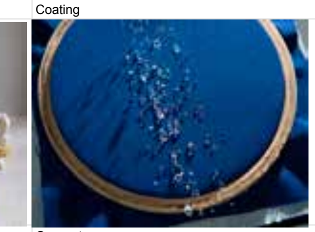
Enhancing natural materials

Applications:
apparel, container, chair, upholstery
Activities:
wearing, containing, seating, decoration
Technical properties:
strong, stiff, tough, ductile, biodegradable, recyclable

Experiential properties:
matte, transparent, rough, light, stiff, warm, proud, mystical, breathable, ecological, high-quality, elegant, coffee smell, leather look
Purpose:
creating biodegrade material
raising awareness of potential materials
to bring together the machine and nature to bring about a new material able to create any product

Enhansing Natural Materials											
	Biology	Composite	Composite	Composite	Composite	Composite	Hybrid		Coating	Pressing	Structural
Application Picture/Sample											
Name	Mycelium leather	Bamboo PLA composites	Coffee Based Material	Blood-related	Artichair	Wiktoria Szawiel	Algae Lab	Mycelium Chair	Organotex	Forest Wool	Truss Me
Manufacturer	MycoWorks, http://www.mycoworks.com/		Coffe Based	Basse Stittgen	Spyros Kizis	Wiktoria Szawiel	Klarenbeek & Dros, Atelier Luma	Eric Klarenbeek & University of Wageningen	Organoclick AB	Tamara Orjola	Sandeep Sangaru
Composition	mycelium, agricultural by-products in carbon-negative process	bamboo fibres as reinforcing agent for polymeric composites	coffee grounds + biopolymer	leftover industry blood	artichoke thistle and biological reisin abstracted from cooking oil	various grasses, plants, wood, wicker and rattan mixed with reisin	biopolymers from algae	3D printing straw + yellow oyster mushroom (fungus)	plant-based catalysts + organic polymers	pine needles leftovers from timber industry	bamboo
(Ram state Picture)	-	-	-	-	-	-	-	-	-	-	-
Technical Properties	strong, flexible, durable, versatile	3x higher breaking point of pla, long lifetime in a solid form without rapid degradation	renewable, flexible, medium weight	hard, smooth, solid	performs like plastic; sturdy, mouldable	sturdy, durable, strong	similar to regular plastics; – composites with sugar cane more durable but less compostable – 100% compostable, less suitable as harder biopolymer	solid, lightweight, strong, durable	repel moisture while remaining strongly bonded to the fabric fibres	strong, versatile, flexible, durable	strong, solid, durable, lightweight
Experiential qualities	pride of animal-free and sustainable material (?)	strong	hard, warm, coffee smell, leather look, matte	black, mystical	-	textures, opacities, revealing (inner patterins)	transparent, rough to touch (printing)	light, sturdy	biodegradable, breathable	biodegradable, ecological, high-quality, elegant look and feel	sustainable
Applications	clothes, linings, decorative, protective layers	structural building composite	– granulate: injection moulding – sheet: vacuum forming	in general: various, these specific objects: eggholder, record, record-player	interior furnishes	furniture collections, vases, containers	tableware, storage systems, waste disposal, etc.	furniture, interiors	covering textiles	textiles, furniture	furnishing systems
Activities	clothing manufacturing		tableware, small objects	exhibiting	replacement for plastics	enhancing + revealing plant fibers	replacement for plastics	exhibit, represent new potentials	enhancing textiles	decoration, resting	enhancing of the material
Ultimate Purpose	natural fibre, 100% biodgradable leather	-	-	raising awareness	Kizis as an advocate for Greek's struggling economy utilized nationally grown crop for consumer products material and biofuel	translating different aspects of landscape into materials, colours, techniques and shapes by combination of natural and artificial	3D Bakery network of object manufacturing and sale shops	to bring together the machine and nature to bring about a new material, and be able to create any product	enhancing textiles	raising awareness about potential material alternatives to artificial fibres	use of the locally resourced bamboo and skills in a sustainable fashion
Process					Seeking a fresh use for byproducts of the plant, designer Spyros Kizis has developed a biodegradable ecomaterial composed of the plant fibers and bioresin—essentially a plant fiber–reinforced plastic. Kizis has used the material to create compression-molded components for a variety of interior furnishings, including a lounge chair, dining chair, and coffee table. Because the new composite utilizes plant components that are not employed to make biofuels, the fabrication process may be creatively coupled with biofuel production to take full advantage of the natural resource. Since the furniture is inherently biodegradable, artichoke thistle seeds are intentionally interspersed within the reinforced material during fabrication. Buried pieces can thus germinate new plants.	Some of the items were cast in purpose-designed moulds, while in other cases the resin was poured over items of wicker furniture.			inspried on nature's own chemistry and the water repallancy of the Lotus flowers leafs. With the use of the patented technology we use biodegradable plant-based catalysts and organic water repellent polymers (hydrophobic) in order to create the water repellent properties to the fabric.	By crushing, soaking, steaming, binding and pressing the needles, Orjola extracts the pine needles' fibre and transforms it into textiles, composites and paper. The process also allows essential oils and dye to be extracted and used.	the strong fibers of bamboo can withstand compression and tensile loads. using the properties of the fibers, 'truss me' was developed on a technique of splitting and laminating the poles with another strip of split bamboo. when the glue cures, the laminated module acts like a truss. the components used for construction are modular and repetitive, and can be produced in batches by a group of craftsmen. the equipment involved for production are basic hand tools. through a modular system of jigs, fixtures and templates, the construction elements were quickly realized and also maintained a formal consistency and quality to the individual components. the furniture has been designed to use locally resourced bamboo and skills in a sustainable fashion.
Enhancement	Controlled biology	Composite of two fibre types				reisin enhancement of wood / wicker or rattan			Wash in or sprayed on fabric to create hydrophobic properties		form of the structure &/or lamination
source + further examples	http://compositeslab.com/composites-101/what-are-composites/				http://transmaterial.net/artichair/	https://www.dezeen.com/2014/07/07/landscape-within-resin-furniture-wiktoria-szawiel/	https://www.ribaj.com/products/replacing-oil-based-plastics-with-algae-klarenbeek-3d-printing-stephen-cousins				https://www.designboom.com/design/bamboo-furniture-systems/

APPENDIX B BENCHMARKING DIGITAL FABRICATION

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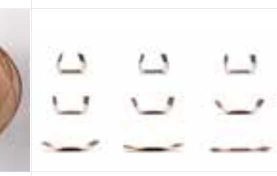
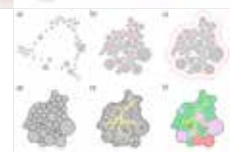
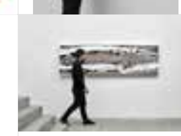
What Values does Digital Fabrication Add to materials?	weight reduction and strength	imitate and optimize how nature creates an object	explore the full solution space for weight reduction and strength	weight reduction and strength	weight reduction and strength, air flow	least walking distance	aesthetics	weight reduction and strength, flexibility, mapped pressure area support	flexibility, mapped pressure area support	aesthetics	programmable behaviour reactive to a given condition (water)	programmable behaviour reactive to a given condition (compression)
	Generative Design/ Shape Optimisation											
Benchmark												
Additional Image												
												
Name	A.I. Chair	Bone Chair	Airbus 320 Partition (Bionic Partition)	Voxel Chair	Back Brace	Evolving Floor Plans	Mashing Mesh Mirrors	3D Printed Midsoles for Runner Shoes		cork thread series of furnitures	Wood Printing	Biomimicry Chair
Date	2019	2006	2016	2017	2016	2019	2016	2015	2018	2018		2014
Designed by	Phillip Stark, Autodesk	Jors Laarman	Airbus Group	Bartlett School of Architecture	Francis Bitonti	Joel Simon	Zhoujie Zhang	Nervous System Studio	Singapore university of technology and design started by professor sayjel vijay patel and architect Nathan Kiatkulpiboone	DIGITALAB	MIT + Christophe Guberan + Erik Demaine + Autodesk Inc	Lilian van Daal
Manufacturer	Kartell	-	Airbus	-		-	-	New Balance	-	-	Self-assembly Lab	Conceptual
Material	plastics	aluminium		melted PLA		-	stainless steel	flexible elastomer	Agilus, Tango, Vero (UV polymers)	cork	Wood grinds + polymer	3D printed
Algorithm/Principles	to rest our bodies using minimum material	What most amazed me about this process is that it uses the very same principle that evolution does in living organisms. Bones in particular are highly efficient in growing internal structures to achieve an optimal weight-strength ratio as they constantly add and remove material in response to stresses from their environment.	The algorithm for the partition frame was based on the growth patterns of slime mold, a single-celled organism that connects multiple points with uncanny efficiency. The algorithm for the structure within the partition frame was based on the grid structures of mammal bone growth, which are dense at points of stress but lighter everywhere else.	Whereas most current 3D printing involves creating forms layer by layer, DCL's software creates designs using one continuous line of material. As well as enabling the creation of more intricate patterns, the software has a functional benefit, allowing designers to create lighter, more efficient forms without using any more material than is necessary for load bearing.	Using digital design and algorithms, Bitonti's studio was able to create a lattice that has 75 per cent less material than its predecessor – the Boston Brace – but still provides the necessary support.	His algorithm transforms a standard floor plan, to minimise the length of corridors and reduce walking time. This results in free-form layouts, with not a square or rectangular space in sight.	mimicing natural movements of water The series consists of five wall mirrors. Each one aims to mimic the unpredictable flow and transition of water in the style of a triangular mesh, which is a type of modelling used in computer graphics.	foam structure provides light weight and strength; The studio carried out a set of experiments at the company's Sports Research Lab in Massachusetts, using a grid of underfoot sensors that recorded the force as the foot strikes the ground and pushes off. "Foam structures are three-dimensional arrays of cells," said Nervous System. "They have a low relative density and are highly porous.	by programming voxel data sets, a user can add microscopic features that help control pressure and temperature. as a proof of concept, voxel harvest was used to design a custom orthotic device to treat a foot injury using compression and temperature control. with textured structures to act as a second skin, microstructures to control elasticity and durability and fluidics to modulate temperature and material expansion, this new technology could enhance patient treatment plans by tailoring multifunctional products to their specific needs.	portuguese based design studio DIGITALAB has created an algorithm that not only creates complex generative forms based on mathematical formulas but also optimizes its structure for future production at the same time. this parametric system allows the creation of multiple shapes and spaces — lamps, chairs, tables and exhibition	Cellulose expands when it gets wet, so wetting wood veneer makes it curl," says Tibbits. "For example, wetting thicker pieces of wood makes them swell with enough force that they used to be inserted into cracks in rocks and moistened to help miners break stone.	"I was testing the flexibility and the stiffness you can get from one material by 3D-printing various structures," said Van Daal. "I did lots of experiments with different structures to identify the kind of properties each structure has." Reducing the density of the material would create more flexible areas for seating, while the amount of material could be increased where greater structural strength is required.
Making Process	Through inputs by Starck, the software went through a process of learning in order to create a chair that was comfortable, structurally sound, and adhered to both Kartell and Starck's aesthetic preferences. The chair is produced via injection moulding, a manufacturing technique that the software was taught about so it would take the constraints of the process into account when coming up with the design.	For the aluminum Bone Chair, the computer-generated result had to be refined for the specifications of aluminum. This resulted in a much more slender shape. We did face yet another challenge, however, for it wasn't going to be easy to produce such a complex organic shape. Especially because assembling it from cast components would leave visible welding stains. Preferably, it would have to be cast in one piece in such a way that no bubbles would show on the surface. Virtually every company we approached refused to take up the challenge, until we appealed to Phil Verdult, who had a small workshop somewhere in the small town of Heerhugowaard. Phil had years of experience with casting processes and had conducted many experiments with new techniques in his workshop, for instance with casting metal in 3D printed ceramic molds. The complex mold could be assembled from such mold parts, and the actual object cast in one go. This resulted in the first aluminum Bone Chair.	3D printing	The designs are then built by a robot that extrudes melted plastic into the air, where it quickly sets as it cools.	3D Print	It imagines the rooms of the building as node genes, each imbued with information such as area. These are joined by connection nodes, which show the rooms need to be positioned adjacent to one another.A mapping process is then used to create an optimal layout. Once the centre coordinates of each room are in place, a polygonal mesh is created to form walls, before corridors are added into the spaces between.	The surfaces of the wall installations are made up of interlocking stainless-steel pieces, which are bent and polished by hand.	3D printing			"We've figured out how to print custom wood grain by taking sawdust and plastic, combining it into a filament and extruding or forcing it out," says Tibbits. "This gives us the freedom to design the direction of the grain, which we can then activate by moisture to produce useful, repeatable transformations, like folding, twisting, curling and so on."	
Application	chair	chair	airplane partition	chair (iconic shape of panton chair)	back brace for scoliosis treatment	floor plan	mirror, art work	shoe sole; shoe			programmable opening windows	In particular, Van Daal looked to nature for inspiration and examined the properties of plant cells, which are able to perform several different tasks.
Activities	sitting	sitting	separating space, anchoring seats for flight attendants			walking on	looking	wear on feet				
E.C.	comfortable, adhered to designer's aesthetic preferences	organic form,	light		fashionable	efficient, shortest walk between rooms	-	adaptable; light	tailed elasticity, temparature,	it's a robust, comfortable material, resistant to light traction and it's also washable, keeping all the original physical properties of cork.		
T.C.	structurally sound	strong; minimum material	strong			-	-	strong			reactive to moisture	
Purpose	collaboration between A.I. and human beings	The purpose of the engine mount design software was to fix specific elements in place while providing optimum strength, using a minimum of materials. This is done by creating a virtual three-dimensional model and simulating the application of stress to specific points on the design. Then the algorithm takes away all of the material that isn't necessarily needed, without weakening the part. What most amazed me about this process is that it uses the very same principle that evolution does in living organisms.	be significantly lighter than the current partition, to meet the goal of reducing the weight of the plane; be strong enough to anchor two jump seats for flight attendants during take-offs and landings; have a cutout to pass wide items in and out of the cabin; be no more than an inch thick, and; be attached to the plane's airframe in just four places.	The software is intended to give designers greater control over the 3D-printing process. Whereas they would usually use software to model an object that would then be automatically "sliced" into layers – or tool paths – for printing, with DCL's invention, they can manipulate the tool paths directly.	the goal was to create a more discrete brace that wearers would feel comfortable in	make floor plans more efficient	research about parametric design, which puts algorithms or rules at the centre of the design process	"New Balance came to us with a problem," said Nervous System. "They wanted to improve the design and creation of their 3D-printed midsoles to better adapt to performance data from runners."	voxel harvest introduces a new prototyping platform to support multi-disciplinary data-sharing and design collaboration with the SUTD digital manufacturing and design center. using authored and automated image data-sets, this system allows teams to create custom orthotic devices with high-resolution textures and microstructures, opening up a whole new world of orthotic care possibilities specific to patient needs.	low-tech material and high-tech process	searching for smart materials — materials that respond and adapt to environments — to make unique new products, but finding ones that are cost-effective and easy to produce has been challenging.	3D-printed soft seat is designed as an alternative to conventional upholstered furniture, which requires several different materials and processes to create the frame, padding and covers.
Impact	the A.I. chair is the first chair designed using artificial intelligence to be put on the market in the world		But Airbus's success in applying generative design and 3D printing also highlights new challenges. The additive manufacturing industry needs to build bigger, faster 3D printers to produce large components with a single printer.	"As designers we can't usually control these or use these tool paths themselves as a medium to design with – its a very top-down process," said Jiménez Garcia and Retsin. "Our software allows designers to bypass this, and immediately design with the tool paths themselves – which gives you access to much more detail and control."		At present, the method doesn't take any external constraints into consideration, such as building costs or the shape of a site. Simon intended it as a simple design exercise. "I imagined more the design than the construction, although it also got a lot of interest from city and residential planners who saw the potential for incorporating optimisation into their work," he explained.	-			in this lamp, the enneper mathematical function was used. with this strategy, it is possible to create various solutions to choose from that make the best of the cork yarn's properties, generating new shapes and spaces that connect creativity, workmanship, technology, and innovation, with the goal of 'transforming the world into a better place'.		
Comments	"Artificial intelligence doesn't have culture, memories or influences and so can only respond with its 'artificial' intelligence. A.I. is the first chair designed outside of the human brain, outside of our habits and how we are used to thinking."	Industrial times and modernist pioneers were all about assembly and standardized parts in a geometric form language dictated by the limitations of industrial machines. In our digital era, however, we are no longer bound by these limitations. With digital design and fabrication tools we can create smarter customized forms that are much more complex.	"I'm a mechanical engineer with more than 30 years' experience," Peter Sander says. "And I see here the biggest change I've ever seen. Every one of us has to understand a new way of working."	This approach is not only more functional in terms of performance, but it also offers designers opportunities to really work directly with incredible amounts of data. "Instead of designing the form of the chair, you design the behaviours and properties of the material directly."		"biological in appearance, intriguing in character and wildly irrational in practice".	-					"When you adjust the structure a little bit you immediately get a different function," the designer pointed out. "In the strong parts I used as little material as possible but enough to still have the good stiffness."
Source	https://www.dezeen.com/2019/04/11/ai-chair-philippe-starck-kartell-autodesk-artificial-intelligence-video/	https://www.jorislaarman.com/work/bone-chair/	https://www.autodesk.com/customer-stories/airbus	https://www.dezeen.com/2017/05/17/robot-made-voxel-chair-new-software-bartlett-researchers-design-furniture-technology-chairs-robots/	https://www.dezeen.com/2017/02/06/generative-design-software-will-give-designers-superpowers-autodesk-university/	https://www.dezeen.com/2019/01/03/evolving-floor-plans-research-joel-simon/	https://www.dezeen.com/2016/05/10/mashing-mesh-mirrors-zhoujie-zhang-algorithms-mimic-water-new-york-design-week-2016/	https://www.dezeen.com/2015/12/06/new-balance-nervous-system-3d-printed-personalised-soles-trainers-footwear/	https://www.designboom.com/readers/voxel-harvest-orthoic-care-11-01-2018/	https://www.designboom.com/design/digitalab-generative-system-materials-processes-06-03-2018/	https://selfassemblylab.mit.edu/programmable-materials/	https://www.dezeen.com/2014/08/05/biomimicry-3d-printed-soft-seat-chair-by-lilian-van-daal/
											https://ideas.ted.com/a-peek-into-the-brave-new-world-of-programmable-materials/	

APPENDIX B BENCHMARKING MATERIAL STRUCTURE EXPERIENCE

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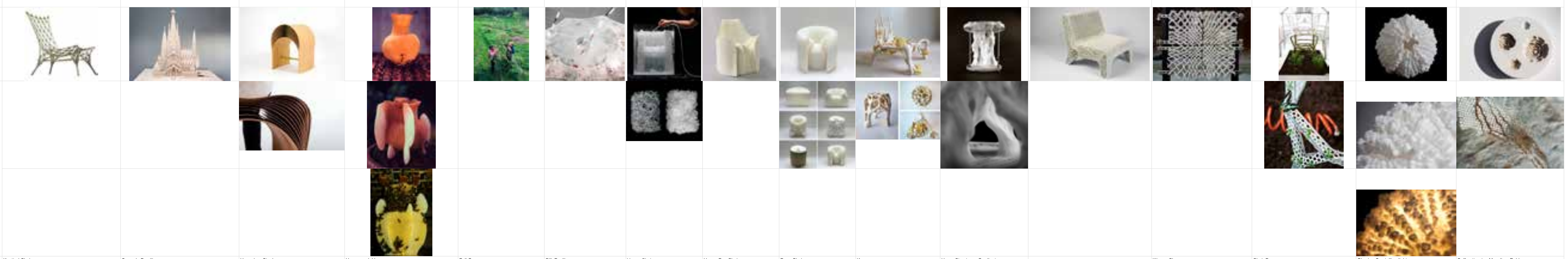

Experience material structure								
Benchmark								
Additional Image								
Name	Knotted Chair	Sagrada Familia	Hangzhou Stool	Honeycomb Vase	Full Grown	Silk Pavilion	Venus Chair	Honey Pop Chair
Date	1996	1883	2013	2007	2012	2013	2008	2001
Designed by	Marcel Wanders	Antoni Gaudi	Chen-Min	Tomáš Gabzdil	Full Grown Ltd.	MIT Media Lab	Tokujin Yoshioka	Tokujin Yoshioka
Manufacturer	Italian furniture brand Cappellini manufactured a limited run of 1000 pieces		-	Studio Liberty	Full Grown Ltd.	MIT Media Lab		
Material	aramid + carbon fibre + epoxy	rock	bamboo	beeswax	Willow/oak	Silk Worm silk, CNC silk fibres	A kind of salt	Tissue papers
Structure	a traditional technique of macrame (a technique for making textiles using knotting rather than weaving)	Catenary Design: a cable or a chain hanging freely and acting under its own weight, supported only at its end points (not in a vertical line) and with no other load, takes the form of a catenary	flexible arcs created by thin bamboo veneers of different length	printed beeswax mould with a honeycomb pattern		a single continuous thread across patches providing various degrees of density.	tetrahedral crystal	layered paper, partially glued, cut, and fanned-open accordion style; seat compressed by body of designer
Making Process	"The design begins with an aramid braided cord around a carbon fibre core that is manipulated in the traditional technique of macramé to form the shape of the chair. The slack threads are impregnated with epoxy and hung in a frame to harden thus using **gravity** to accomplish its shape."	Gaudí's design is established by a model with hanging chains, a so called catenary design.	The Hangzhou Stool consists of 16 layers of bamboo veneer of the thickness of 0.9mm. Each one of the 16 bamboo veneers is different in length. They are bent in an arc shape and glued together at the last 25cm of each end. One piece of raw bamboo stick penetrates in the veneers and combines the two ends of the stool.	The vases are created by placing a basic beeswax mould printed with a honeycomb pattern into a beehive. The bees then do the rest. It takes 40,000 bees a week to make each vase	The process starts by training and pruning young tree branches as they grow over specially made formers. At certain points the branches are grafted together so that the object grows in to one solid piece. After it's grown into the expected shape, people continue to care for and nurture the tree, while it thickens and matures, before harvesting it in the Winter and then letting it season and dry.	the overall geometry of the pavilion was created using an algorithm that assigns a single continuous thread across patches providing various degrees of density. Overall density variation was informed by the silkworm itself deployed as a biological printer in the creation of a secondary structure. A swarm of 6,500 silkworms was positioned at the bottom rim of the scaffold spinning flat non-woven silk patches as they locally reinforced the gaps across CNC-deposited silk fibers.	let the salt crystalize in water, on a shape of the chair; VENUS takes shape by making the tiny crystals grow in an aquarium, half controled, half natural	It is made of the tissue-thin glassine honeycomb paper used for Chinese paper lamps. Layers of paper are laid flat, stacked, and a single curved cut is made to shape the back and seat. The form fans out, accordion-style, into a surprisingly strong and durable structure.
Application	chair	church architecture	stool	vase	chair, lighting, table	digital and biological fabrication on product and architectural scales	chair	chair
Activities		housing		keep flowers	sitting, seeing	sheltering	sitting	customizing, sitting
E.C.	surprise, romantic, humane, decorative, iconic, handcrafted, delicate		When sit, the more weight the stool receives, the deeper the arc will be bent in the center, and therefore the more elasticity the user will feel.	unique form of each vase, unique color and smell, depending on flowers of that season	Natural, crafted, carbon-absorbing		makes its appearance over time as if the goddess herself gradually emerges from water.	surprise, customizable
T.C.	rigidity provided by epoxy, extremely durable and light "The knotted pattern forms a space frame structure that is strong enough to support the weight of the person sitting in it." "It's stable enough to hold a heavy guy, keeping the whole thing up and making it strong."	load-bearing, no bending moment	-		ergonomical, fastened in one solid piece stiff, durable	delicate but strong; combination of digital and biological fabrication		strong
Purpose	"Exploring new hi-tech materials and manufacturing techniques" (Dezeen.com) "I understood that this carbon fibre material is a textile. Instead of making carbon fibre sheets that we then bend to create volumes, I wanted to create a textile." (Wanders)		To express the FLEXIBILITY of Hangzhou city, where the designer grew up	new production technique of collaborating with bees	making the method open source (from the ted talk)	A showcase of the relationship between digital and biological fabrication on product and architectural scales	"The work is like my message for the future."	
Impact	becoming an icon and a point of reference for design and the years to follow. Part of the permanent collections of the Museum of Modern Art, New York, the V&A Museum, London and the Stedelijk Museum, Amsterdam, among others, the 'Knotted Chair' is a modern miracle of transparency, a highlight of the international design world and a sought after collector's item.		-	Libertiny's "collaboration" with honey bees pushes the boundaries of so-called conventional design by defying mass production and enabling nature to create what would typically be considered a man-made product. Studio Libertiny's bee vase not only tells the story, but does so in an ecologically derived, natural way that concedes the human manufacturing process to something simpler and more beautiful.			This natural crystal chair, which is formed using the laws of nature and embodies a beauty born of coincidence, pushes the boundaries of creativity.	
Comments	"We had to make this chair in mid air, so we had to work with gravity," Wanders explains. "We hung our knotted structure in the frame. Strangely enough, that piece of rope became stable and we could sit on it. It was a little miracle."		"Congratulations on a beautiful stool! This is exceptional design. If durability can be demonstrated, this could become a very sought after piece of furniture." (petre.m, Designboom blog comment)	a case of slow prototyping				
Source	https://www.marcelwanders.com/work/knotted-chair	http://www.structuralice.com/gaudi-s-sagrada-familia.html	https://www.chen-min.com/hz-stool		http://fullgrown.com			
	https://www.dezeen.com/2015/12/14/video-interview-marcel-wanders-knotted-chair-most-loved-movie/		https://www.designboom.com/design/hangzhou-stool/	https://www.dezeen.com/2007/08/30/the-honeycomb-vase-2007-by-studio-libertiny/			https://www.core77.com/posts/11364/growing-furniture-the-venus-chair-by-tokujin-yoshioka-11364	https://collection.cooperhewitt.org/objects/18714653/

Experience material structure								
Benchmark								
Additional Image								
Name	Pane Chair	Krown	Hemp Structure - Gradient		Woven Clay	Chair Farm	Glowing Crystalline light	Self-patterning Mycelium Rubber
Date	2006	2013	2015		2014	2018	2012	2016
Designed by	Tokujin Yoshioka	Klarenbeek & Dro	Gianluca Tabellini	Lilian van Daal	Jared Freidman and his classmates	Studio Aisslinger	Daniel Macdonald	Carole Carlot
Manufacturer		Klarenbeek & Dro			Harvard University	Studio Aisslinger		UAL research project
Material	polyester elastomer	Mycelium & straw mixture	Mycelium, hemp	3D printing material: nylon	Clay	Bamboo	purified salt	mycelium
Structure	Natural structure of a baked roll of the material	organic 3D printed form	mycelium grown on hemp structure	bone structure	Weaving	not specific	salt crystal	self-patterning structure
Making Process	A semi-cylindrical block of fibers is rolled, inserted into a paper tube, and by baking it in a kiln for about 30 minutes, the fibers memorize the shape of the chair. It is an entirely new type of chair in which the fiber itself is the structural body and which feels like sitting on air.	Instead of using plastics, we pile up local land-waste, and the mycelium binds it all together. The machine simultaneously prints the infill and outer shell, which prevents its fresh mycelium and straw mixture from falling apart. After printing, we only have to wait for the structure to grow and gain its strength, which only takes a few days.	A non-uniform hemp pattern let the mycelium to grow by a gradient of density	Van Daal was able to create these varying zones of stiffness by imitating plant cell structures in the natural world.	The team appropriated a robotic arm from a factory floor, bolted a giant clay-filled syringe to it, and employed a printing process developed by the Harvard Graduate School of Design Robotics Group. He created CAD files that specified paths for the robot to follow and as it progressed clay was squeezed like toothpaste from the metallic cylinder onto an irregular surface forming a two-foot square panel. Half-inch thick clay coils were woven, braided, and built-up in patterns on the panel, but despite their futuristic pedigree they were actually inspired by much older manufacturing processes. After the pattern was completed the panel's edges were trimmed, they were fired in a kiln, and assembled on a steel scaffold.	The chair is no longer produced in the classical sense of the word. Instead, it grows of its own volition in a greenhouse or on a field. When it has reached maturity, the steel corset is opened and removed, revealing a naturally grown chair.	MacDonald mimicks the same conditions of Yellowstone in his studio/salt nursery, where each lamp is painstakingly created by pouring purified salt over pre-made forms, requiring up to a week to form the crystals evident on each unique sculpture. Different forms are categorized as different species like "Orbis," "Chyrsalis" and "Occulus." Growing shio sculptures reliably and without unsightly birth defects requires precise and stable control of the mechanical, thermal, and chemical properties of the growing environment.	Various mycelium are cultured on a variety of materials that either harness, support or resist the fungi's growth; these include coffee grounds, agar, hemp, sisal, soya bean fibre, raw silk, organic cotton and linen. Developments include a mycelium lace, where the living material serves to reinforce and mend the lace it grows on, and a self-patterned mycelium 'rubber'. The latter is as flexible as rubber, and exhibits 'floral' patterns which are not created by moulding, but by the mycelium itself, as it grows on waste coffee substrate. This is the first known example of a self-patterning mycelium material.
Application	chair	chair, stool		chair	architectural facades	chair	light shade	
Activities	sitting	architype of functional product		sitting	seeing	sitting, conversation starting	getting light from	
E.C.	soft, ductle, elastic, strong	After use, the product is fully compostable, and can be disposed without harming the environment.	aesthetical	soft, flexible seat	novel	radical	watching the salt grow is wonderful otherworldly	
T.C.			Self-standing	a flexible seat and a rigid base				
Purpose	new manufacturing technique,	Alternatives for 3D printing materials	to create a protocol where mcelium grow on the substrate that is arranged in a preset structure	investigating alternative production methods for upholstered furniture, which is usually very resource-intensive to make	Turning an industrial robot into an artistic tool required fine tuning of the controller software as well as the mixture of clay it extrudes. Friedman's goal was to create subtle variations in the panels while maintaining tight control at points where the panels would be anchored to the buildings."The biggest challenges involved striking the right balance between what was controlled and what was uncontrolled," he says. "We wanted to have enough control to print a panel with a fair degree of accuracy to the initial design, but we also wanted to allow for some of the irregularities to occur that make each panel unique."	A new way to invert production in furniture design back from globalized serial manufacturing to resource-conserving local production.	The idea: let beautiful physics create beautiful objects. The manifestation: living crystal beings, frozen in time, and filled with light.	Mycelium Textiles is to develop biodegradable, compostable textile coatings to replace finishing processes derived from oil, instead using manipulated mycelium growth.
Impact	It is Tokujin's idea of a structure of the future - not to secure strength using hard materials, but to gain strength by spreading the stress.	The plant material produces oxygen during its life cycle, and our production process eliminates the necessity of heating materials in the printing process, thus reducing the use of energy. Adding up those two facts, combined with the use of local resources and production, it becomes possible to create products with a negative 'carbon footprint'. Instead of wasting less, we strive to absorb emission.		can be adjusted on different parts to be harder or softer				
Comments		We are the first in the world to 3D-print living mycelium, using this infinite natural source of organisms as living glue for binding organic waste. Once it's full-grown and dried, it turns into a structural, stable and renewable material. Combined with 3D-printing it gives us tremendous design freedom'' - Erik Klarenbeek "When you dry it out you have the straw kind of glued together by the mushroom," Klarenbeek said. "You have this strong, solid material that is really lightweight and durable." A thin layer of printed bioplastic covers the structure of the chair to contain the growing fungus. Straw was used as a substrate since the fungus used in the project - the yellow oyster mushroom - likes to grow on straw.		She wants to develop it further, using more bio-materials	Combining dozens of these panels provides architects with an opportunity to create architectural facades that have the warmth of handwoven fabrics while stretching for hundreds of square feet. Friedman and company have no plans to commercialize their creations, but are excited to have wrung new possibilities out of old hardware.		Every shio is unique, but growing many from a similar form allows them to be grown more easily. Species are families of individuals grown from similar skeletons. The individuals shown here are merely exemplars of their species. There is no prespecified limit on the number of individuals of any given species that might be grown, but because species change and differentiate over time, each individual is a physical snapshot of a unique point in a larger evolutionary history much as it is also a physical snapshot of unique point in a continuous crystal growth. Each individual is identified with a universally unique identifier (uuid) which links the individual to its maturation records and allows it to be placed precisely in the phylogenetic tree of shio.	
				http://archinew.altervista.org/2015/01/30/lilian-van-daals-3d-printed-biomimicry-chair-shows-off-a-new-way-to-create-soft-seating/			https://www.treehugger.com/sustainable-product-design/crystalline-lights-are-grown-salt-daniel-macdonald.html	https://www.franklintill.com/journal/living-materials
Source		http://www.ericklarenbeek.com	http://mycelium-tectonics.com/category/aesthetics/	http://www.biomimicrybe.org/portfolio/front-page-images/	https://www.wired.com/2014/06/harvard-robot-whiz-invents-a-way-to-weave-build-facades-out-of-clay/	https://www.aisslinger.de/chair-farm/	https://www.kickstarter.com/projects/1645384643/shio-otherworldly-lights/description	http://ualresearchonline.arts.ac.uk/10405/

APPENDIX C EXPERIENTIAL CHARACTERISATION

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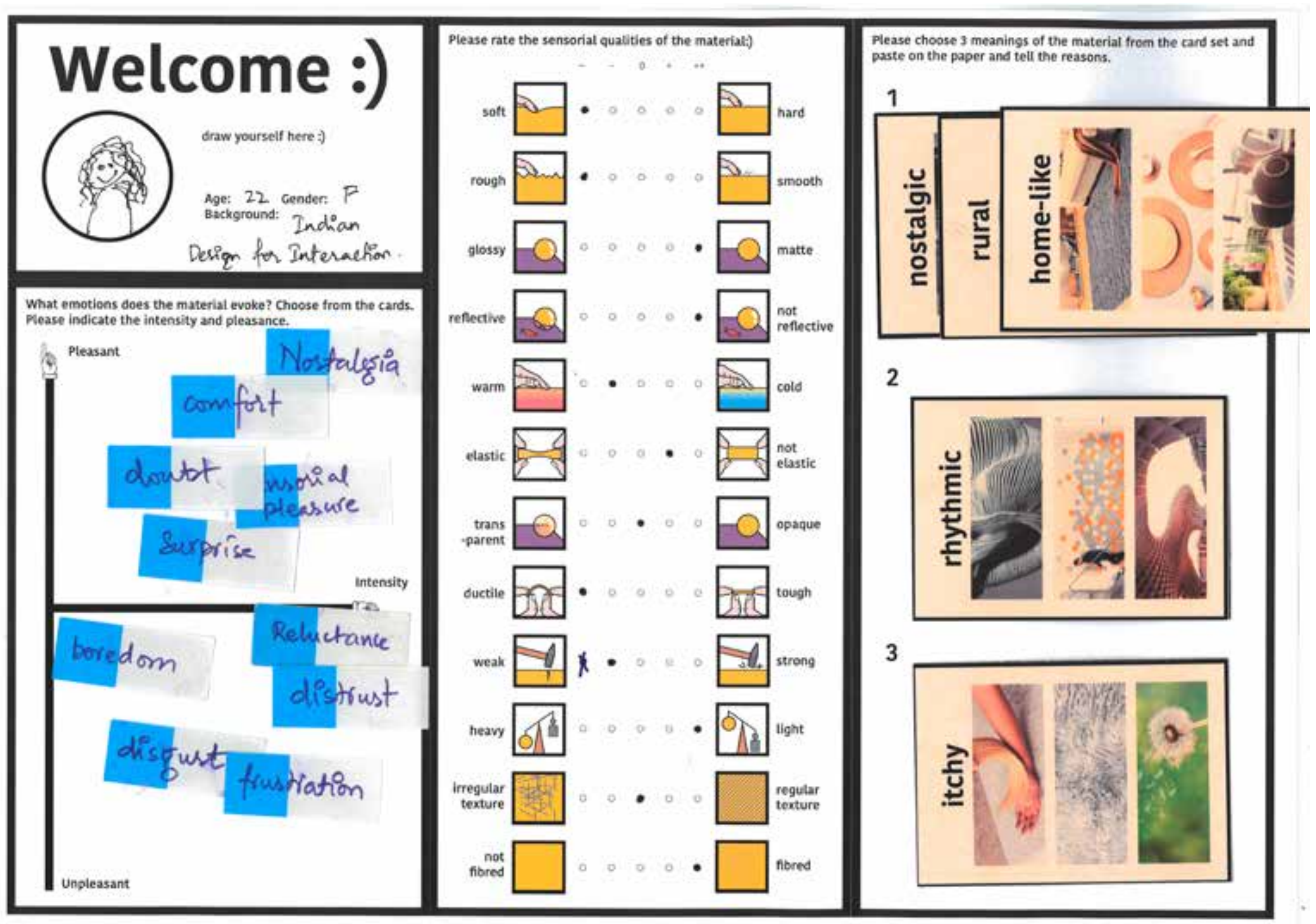
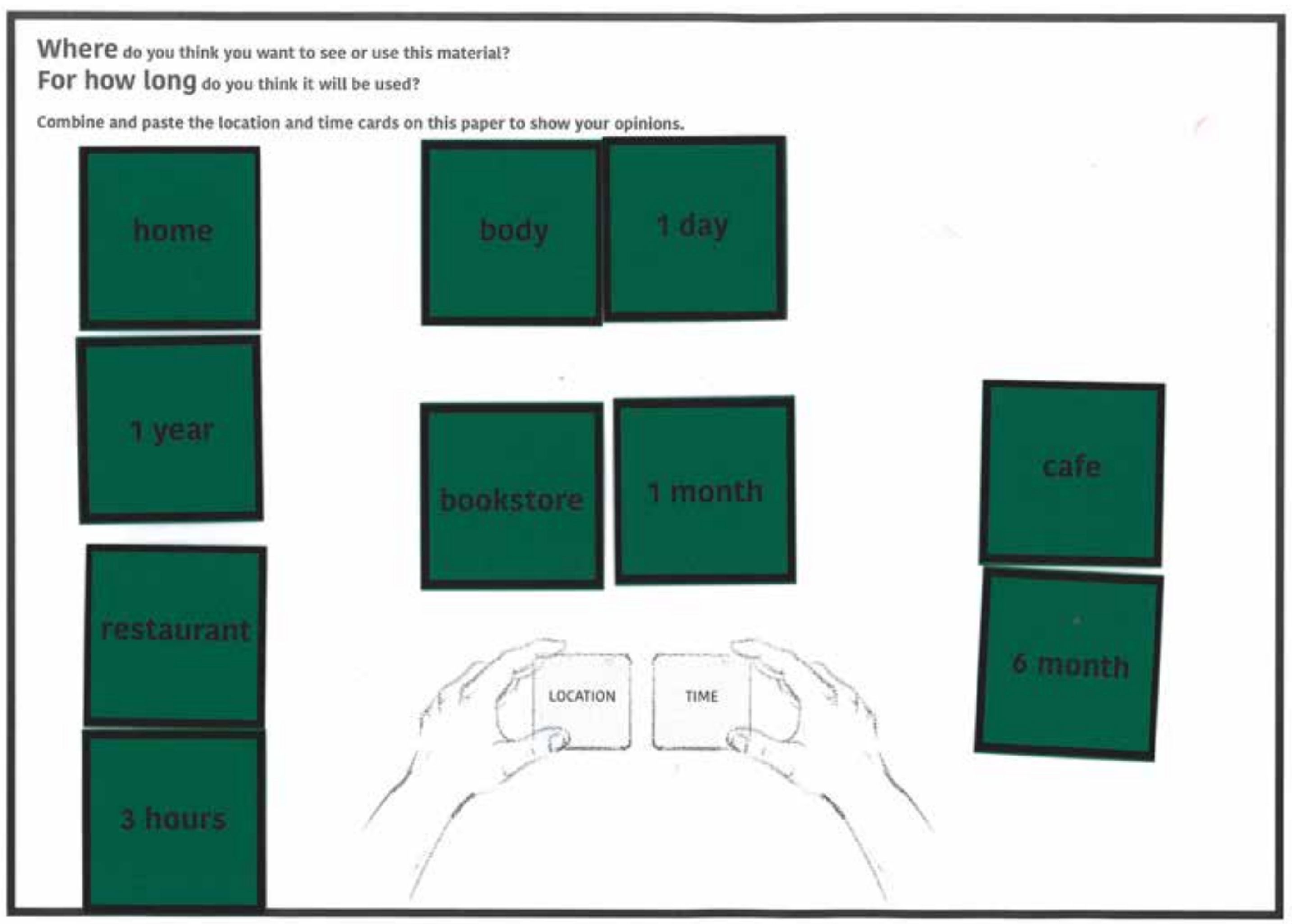


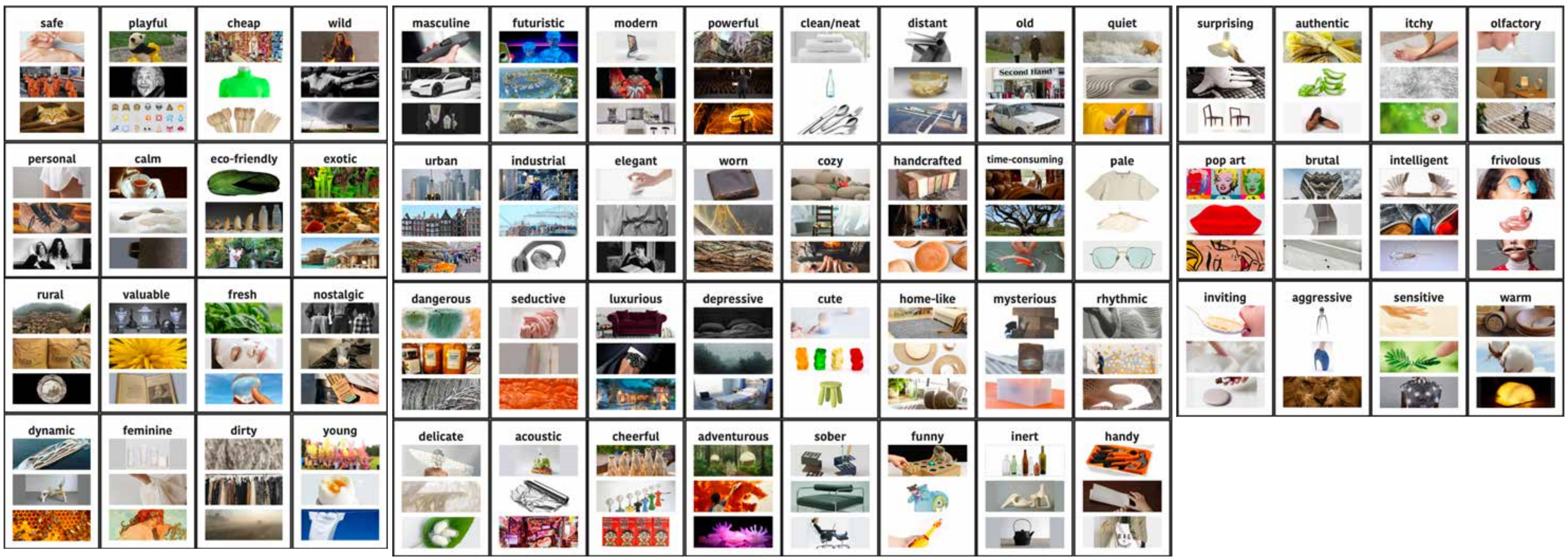


An example test sheet from one participant

frustration	love	boredom	amusement	disappoint -ment	surprise	reluctance
confidence	confusion	enchant -ment	rejection	respect	disgust	attraction
melanchony	curiosity	distrust	fascination	doubt	comfort	nostalgia
dreaminess	gratitute	energetic	satisfaction	sensorial pleasure		

library	home	restaurant	cafe	office	train	bridge
bike	car	sidewalk	beach	museum	sports	canal
hospital	body	bar	super -market	3 hours	1 day	1 week
1 month	6 month	1 year	bookstore	park	IKEA	grassland

left: Emotion cardset,
below: Interpretive cardset
right: Place & time cardset



APPENDIX D IDEATION SHEETS

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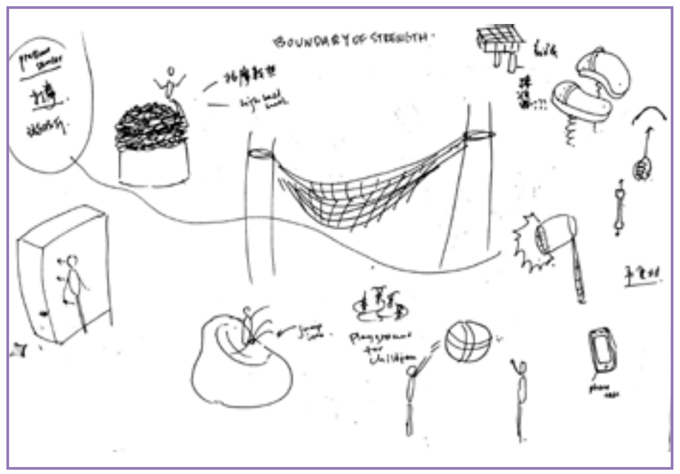
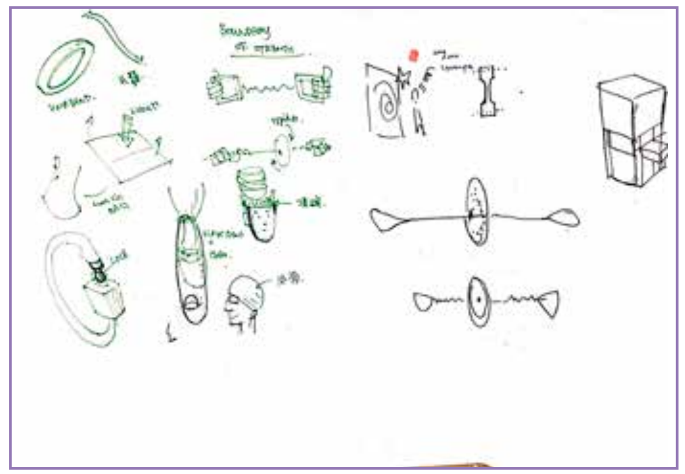
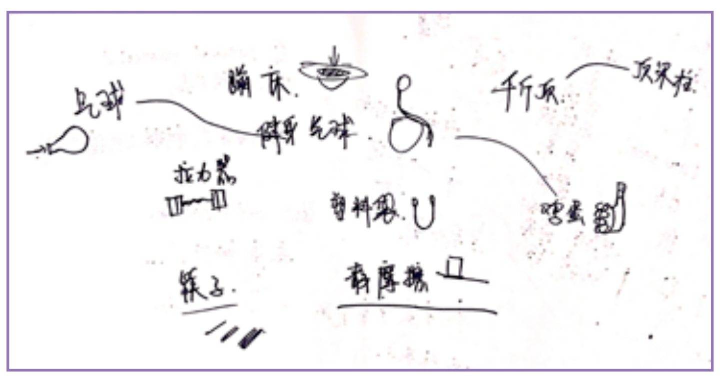
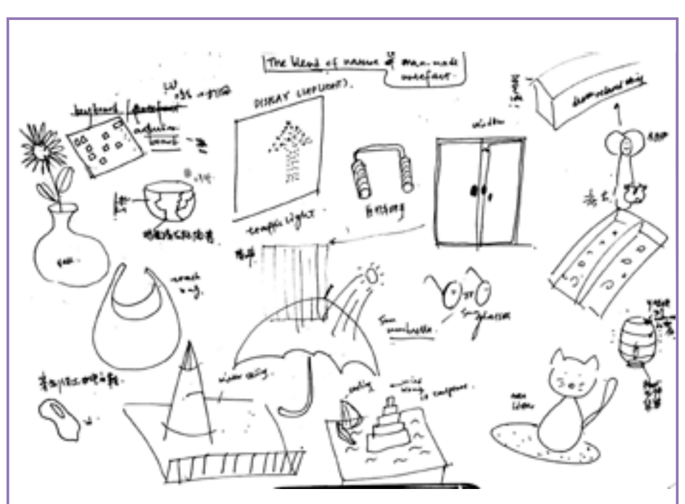
Ideation of Strength Before Seeing the Samples

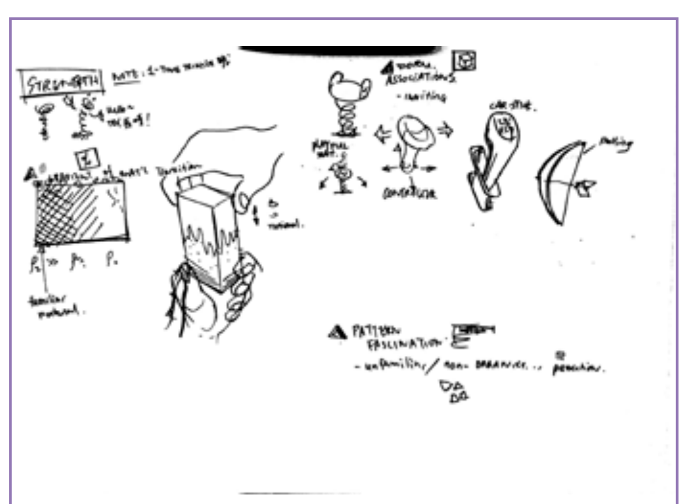




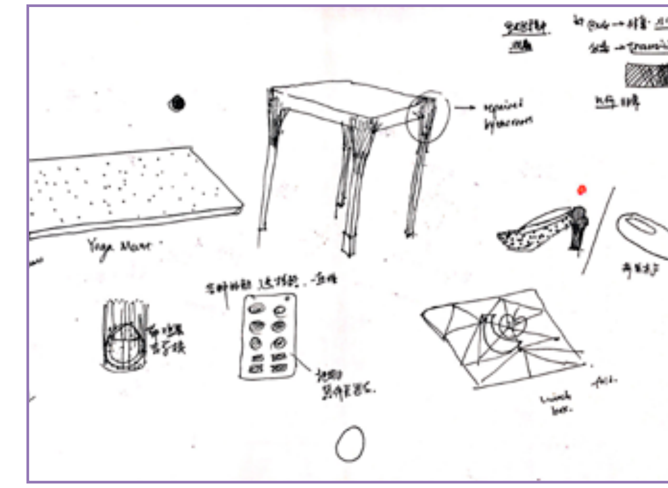


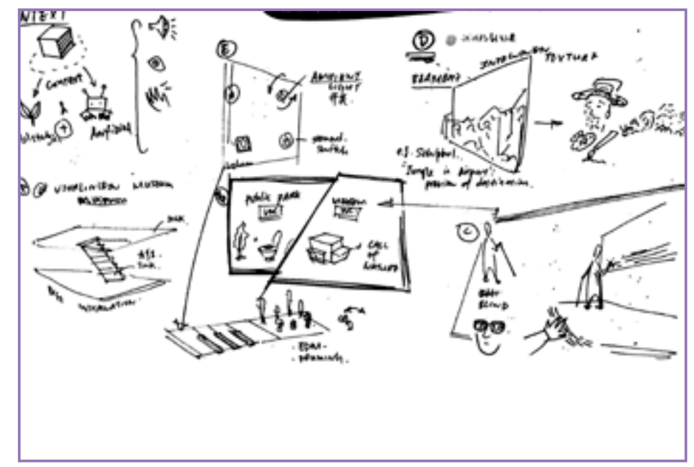
Ideation of Strength After Seeing the Samples

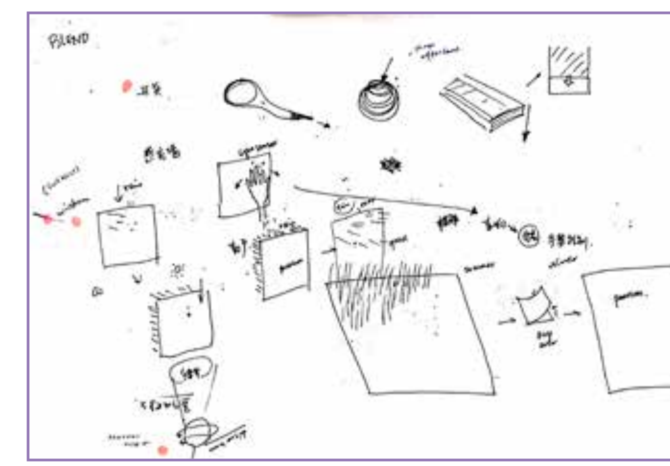




Ideation of Blend of Nature and Man-made Before Seeing the Samples







Ideation of Blend of Nature and Man-made After Seeing the Samples