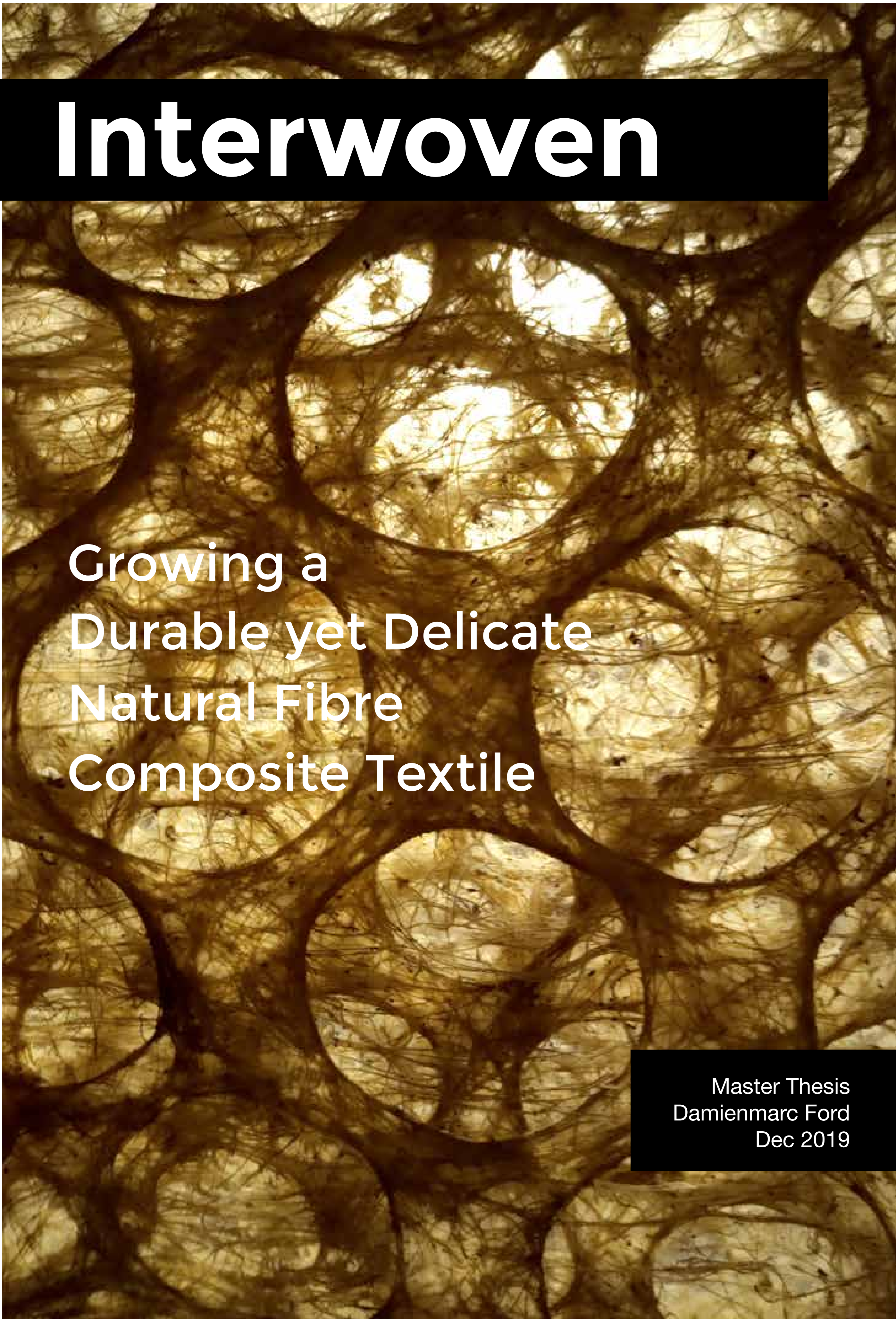
Interwoven



Growing a Durable yet Delicate Natural Fibre Composite Textile

Master Thesis

Damienmarc Ford

Dec 2019

“With growing recognition of ecological failure, our survival demands we consider ethical responsibility in the direction of research and development of new realities”

Dalai Lama

Interwoven

This project 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, therefore some research results have been excluded from this report.

Damienmarc Ford (4660986)
Msc Design For Interaction
10 Dec 2019

Delft University of Technology
Faculty of Industrial Design Engineering
Landbergstraat 15, Delft (The Netherlands)

Supervisory team
Chair: Dr. E. Karana (Delft University of Technology)
Mentor: Dr. Marieke Sonneveld (Delft University of Technology)

In collaboration with
Creator of Interwoven
Diana Scherer
http://dianascherer.nl

Material Experience Lab
http://materialsexperiencelab.com

Preface

My motivation throughout this project has been to bring people closer to nature, where natures craft collaborates with my own, to actualise the theory of Materials Experience and get people to think about potential ways to fabricate materials and meaningful experiences that are more in alignment with the environment.

I'd like to dedicate this thesis to Malcolm Tailor (1953 - 2019), dear friend, family member and inspirational radio DJ for Dubaieye, RIP.

The results of this thesis could not have been achieved without Diana Scherer. I'm very grateful to have been able to learn from her and to collaborate with her with this new age material. I've taken a lot of pleasure out of nurturing the growth of the material from seedling to harvest. I look forward to the developments of Interwoven being a bio-textile of the future.

I want to thank my supervisors; Elvin Karana for giving me the ability to connect with the Materials Experience Lab, learn from her about materials experience knowledge and for providing the opportunity to work as a student assistant. Also for broadening my horizons by supporting a visit to Bangladesh. Marieke Sonneveld for her honest feedback, advise, helping me structure my thoughts and constant enthusiasm. I appreciate the support from both of you for the development of this project. I'd also like to thank Sepideh Ghodrat and Mascha Slingerland for their technical support. To all my dear friends for their positive energy and family-like care. Special thanks to my best friend and partner Celeste Volpi for her endless belief in me and your ability to help me see the forest from the trees.

Executive Summary

This is the final thesis of the faculty of Industrial Design Engineering of Delft University of Technology in collaboration with visual artist Diana Scherer. The project approach follows the Material Driven Design method (Karana at al., 2015) for a material called Interwoven developed by Diana. The material has drawbacks and is too fragile to be an applicable textile material, but it has great potential to be a sustainable substitute material for product design and textiles industry. The goal of this project is to *improve the durability* of Interwoven. Through the lens of materials experience conduct experiential analysis' to identify how the material makes people 'feel, think and do', to find an application as a textile with delicate and durable experiential characteristics.

The main research question is formulated as: *'how can Interwoven be strengthened towards being a durable textile comparable to other natural fibre textiles?*

To understand the material Interwoven a tensile test was conducted along with research into root biology, which supported the problem definition of the materials fragility. An experiential characterisation study was conducted through the lens of materials experience, which identified that the roots evoke a strong connection to nature due to its origin. It became a personal motivation to keep this as a desired requirement of the experience the material elicits. That being, *connecting people to nature, where nature is the main crafter.*

In previous research a framework of variables was developed to structure the development of Interwoven. Guided by this materials tinkering taxonomy, more than 50 experiments and iterations were conducted to investigate developing the durability of Interwoven. Along side tinkering sessions, a literature study was conducted to create understanding of the field of bio-composites and the state of the art of bio-textiles, along with benchmarks to identify interesting opportunities for applications.

Particular material samples were selected to conduct further experiential studies and technical studies. Of particular interest were the use of bioplstics to act a matrix to create a bio-composite.

Through the material studies it was discovered that the bioplastic samples were evocative of positive memories, images and emotions reminiscent of the past, often being interpreted as natural, nostalgic and handcraft due to the imperfect aesthetic the root architecture afforded. The most unique characteristic was derived from the origin of the material being grown. People appraised the material positively due to their own systemic reasoning of a need to move towards more environmentally benign materials and production for the future. However they were apprehensive in their performative interactions because of an unfamiliarity with the material, which led to negative emotions to do with insecurity about the technical performance of the material to withstand forces such as pulling and tearing.

The potential of the material is in the experience it elicits and the ability to manipulate the roots into a desired 2D form. To create durability Interwoven sheets are layered with a unidirectional fibre arrangement, a homogeneous interwoven matt, combined with pectin bioplastic to create a bio-composite. Patterns from nature were used to symbolically represent the connection to nature. It was also noticed that delicate interpretations were evoked when the material had some holes and that it was semi-transparent, and so these features were kept to keep a balance of durability and delicateness.

The technical qualities, experiential qualities and the benchmark were combined, which led to a define Materials Experience Vision as follows:

I want people to trust the interwoven 'bio-composite' by designing a bag to represent its strength and exhibit the delicate root architecture through artisanal craft, bonding the wearer to a deeply evocative connection to nature.

With the vision as the basis for idea generation low fidelity paper prototyping and material development was explored. The final concept is a tote bag design that is grown into 2D form and simultaneously folded into the desired form while adding the bioplastic matrix. Further technical testing was done to characterise the compositional structure. A final material demonstrator is delivered.

This thesis concludes with a evaluation of the design goal and a set or recommendations for further research.

Contents

1

Project Description

This first chapter gives an introduction to the project. It explains 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.

"For many generations… they obeyed the laws and loved the divine to which they were akin… they reckoned that qualities of character were far more important than their present prosperity. So they bore the burden of their wealth and possessions lightly, and did not let their high standard of living intoxicate them or make them lose their self-control…

But when the divine element in them became weakened…and their human traits became predominant, they ceased to be able to carry their prosperity with moderation."

Plato, Timaeus - A description of the reason for the fall of mythical Atlantis.

Michelangelo Pistoletto
Venus of the Rags
1967 - Tate Modern

1. Introduction

The world we live in is one of over consumption. In 1963 Packard coined the phrase throwaway society. He warned that a society with vested interest in over-consumption would lead to significant social, economic and environmental implications.

Today we are all familiar with the ecological crisis, its not a case of confronting bizarre or ineffable evidence. We know we have reached a turning point. The momentum of post industrialisation has brought us to a collective awakening of our unconscious impacts on the Earth's planetary boundaries and capacity to sustain life. *According to the United Nations (2015), we have a 12 years to limit climate change catastrophe.* By 2030, emissions of carbon dioxide have to be cut by 50% and come down to zero by 2050. It is apparent that current patterns of consumption and production must change in order to sustain life for humans and conserve the biodiversity of the planet.

In 2015, the United Nations launched its Sustainable Development Goals (SDG) to address critical environmental challenges. Of the 17 specific goals, SDG 12 declares new targets for "sustainable management and efficient use of natural resources" by 2030 (United Nations, 2015, p. 26). However, as it stands today current consumption outstrips the resources available, requiring 2 Earth's by the year 2030 (The Global Foot Print Network, 2018).

The Current Textiles System

The textiles industry is a very unsustainable industry that depletes and wastes the natural resources that we depend on to live.

"Second to oil, the textile industry is the largest polluter".

Forbes, making climate fashionable (2018)

The current system for producing, distributing, and using textiles is reliant on a linear model that does not integrate the true cost to nature. In 2013 the European Commission stated the textiles industry is ranked 4th in terms of environmental impact. Now it is the second largest polluter, second to oil due mostly to poor utilisation (Forbes, 2018).

"Up to 80% of the textiles are land filled each year".

Secondary Materials and Recycled Textiles Association (2019)

Relying mostly on non-renewable resources – 98 million tonnes in total per year – including oil to produce synthetic fibres, such as polyester, fertilisers to grow cotton, and chemicals to produce, dye, and finish fibres and textiles. (New Textiles Economy, 2017). With low rates of utilisation and recycling up to 80% of textiles are landfilled each year (SMART, 2019). As well as 20% of industrial water pollution globally is attributed to dyeing and treatment of textiles (Kant, 2012). This linear system puts massive pressure on resources and the natural environment.

Improvement in the sustainability of textile production and exploring cleaner systems of productions is important to us all for maintaining the natural world.

Emerging Textiles Design

There is increased consciousness toward sustainability in the textile industry with many companies and designers embracing sustainable values. New economic models such as circular and bio-based industries are emerging based on cradle - to - cradle and Design for Sustainability (D4S) principles, regarding textile fibres as nutrients rather than waste (Mc Donough and Braungart, 2002). These companies support the transition towards an ecological sustainable future and bioeconomy. Which is, "knowledge based production and utilisation of biological resources, processes and principles to sustainably provide goods" (Global bioeconomy summit, 2015). The bioeconomy is a model for a post-petroleum society, and today, "more than forty countries have integrated bioeconomy in their policy strategies" (Global Bioeconomy Summit, 2015, p. 4).

A method of engaging with the bioeconomy is through the process of biofabrication, which is the process of producing complex material through the growth of living organisms (Collet, 2018). Examples include Bolt Threads, who created a bio-fabricated silk. Engineered "from scratch based on proteins found in nature" (Stella McCartney & Bolt Threads, 2017). Modern Meadow's Zoa (2017), with "the first ever bio-fabricated leather" derived from mycelium.

In the context of an emerging organism industry, designers and artists are starting to engage directly with the discipline of biodesign (Myers, 2012), which intersects biology and design principles for material creation.

Artist Diana Scherer biofabricates a textile out of plant roots she calls *Interwoven*. She nurtures the plant growth, while simultaneously guiding the final outcome. Its a convergence of growing and shaping that requires understanding the parameters of plant growth. By optimising these parameters she can effect the living systems properties, and effectively removes many of the unsustainable steps required for the production of natural fibre textiles.

This report proposes a vision for the textile called Interwoven, aligned with cradle - to - cradle and Design for Sustainability (D4S) principles.

Natural Fibre Production

The textiles industry predominately uses oil to develop synthetic fibres, with more than 60% of textiles being polyester. The remaining 40% is dominated by cotton (24%), (New Textiles Economy, 2017). One might ask, if we focus on developing natural fibres textiles, instead of synthetics, would this be more sustainable?

As mentioned in the previous paragraphs the textiles industry relies on a linear system. Natural fibres utilise petroleum based processes that are resource hungry and inefficient at all stages of the production chain. Some negative consequences of cotton production are indicated below:

- Cotton production uses 2.5% of the world's arable land, and accounts for 16% of all pesticides used.
- Cotton is estimated to require 200,000 tonnes of pesticides and 8 million tonnes of fertilisers annually.
- In India 50% of all pesticides are used for cotton production.
- 1 kilogram of cotton textiles uses up to 3 kilograms of chemicals.
- Up to 4,300 litres of water are used to produce 1 kilogram of cotton fibres.
- Dyeing and finishing can use around 125 litres of water per kilogram of cotton fibres.
- Many of the key cotton-producing countries are under high water stress, including China, India, the US, Pakistan, and Turkey.
- The use of chemicals is prevalent at all stages and summarised to the right in figure 1.

Source: Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future, (2017, http://www.ellenmacarthurfoundation.org/publications).

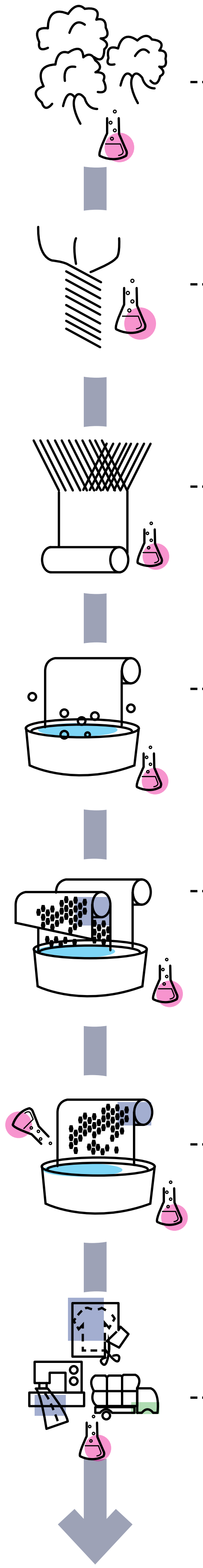


Figure 1: Illustration of chemicals prevalent in production of cotton.

Fibre Production
Cotton is enormously resource-intensive, with high inputs of water, pesticides, insecticides and fertilisers.

Yarn Production
To increase the strength, cohesion and reduce friction during the spinning process, spinning oils are added.

Fabric Production
Depending on production process to increase the strength and reduce friction, sizing chemicals or lubricants or solvents and binders are used.

Pre-treatment Process
Textiles need to be prepared for dyeing. This depends on the blend of fibre, and how it will be treated. Can include; detergents, solvents, enzymes, bleaches, bases and acids.

Dyeing and Printing
The most common way to print is to use pigment prints, where polymeric resin is used, the PVC-based paste contains hazardous chemicals, such as phthalates.

Finishing Treatments
Depending on the desired effect, such as flame resistance, water resistance, antibacterial treatment, protective coatings or anti-static, a diverse range of chemicals are used.

Manufacturing & Transport
Finally the textiles are tailored, cut and sewn into the desired form. Biocides are used in transportation to prevent moulding.

Source: Get familiar with your textile production processes, chemsec. (Available at: http://textileguide.chemsec.org/find/get-familiar-with-your-textile-production-processes/#pre-treatment, 2018)

1.2 Interwoven

The opportunity to co-create with nature and fabricate materials from living organisms offers advantages for product design, such as novel aesthetics, material functions, diverse expressions of greater sustainability.

Introduction

We must strive to protect the biodiversity of this planet. The accelerated turnover of products in our today's consumer culture has led to an overexploitation of resources and caused an ecological crisis. The increase in global population and affluence has inflated consumption to a level that is not in the long term sustainable (Ashby, 2013).

Achieving genuine sustainable development requires that we 'change patterns of consumption and production, particularly in industrialised countries (Schoon, 2013). This emphasises the need for product designers to contribute to the design of more sustainable, circular and alternative material practices that are in pursuit of environmental advantage and cleaner systems of production (Camere et al., 2018). Since we interact with materials through products it is designers who shape the experiences of people, which makes it important to consider how and why we are doing things (Bezooyen, 2014) as these can determine the environmental and social impact on society.

The use of bio-based materials in product design (Ashby, 2013) is one such strategy that aims to tackle this problem. In particular, growing design is an emerging new design approach at the confluence of materials science, biology, arts and design. Changing the role of the designer from passive recipient of materials to an active maker of materials (Karana, et al., 2015, Myers, 2012) and has potential for a more sustainable future that utilises the production of local resources and connects designers intimately with the biosphere.

Growing Design

This approach is called Growing design, which is distinctive within the notion of Myers' (2012), BioDesign.

Growing Design moves beyond the drop-in replacement of existing materials technologies (Camere, 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.

Since materiality highly contributes to the definition of Product Experience (Desmet and Hekkert, 2007) the concept of Materials Experience arises. Defined as "the experience that people have through and with materials" (Karana, 2009; Karana, Pedgley, and Rognoli 2015), considering senses, meanings, emotions, and ways of doing (Giaccardi and Karana, 2015).

Growing design is a phenomena grouped under the concept of 'emerging materials experiences' because it is scarcely understood in design literature (Karana, et al., 2017), and so there is a need for further theoretical discussion about Growing Design through the lens of materials experience as a strategy that can bring these novel materials closer to society and shorten the gestation time of materials innovation (Karana et al., 2015).

Sample of Interwoven; source: https://materialdistrict.com/material/interwoven/

Image: Diana Scherer holding a sample of Interwoven

The Roots of Making

Diana Scherer *(dianascherer.nl/)*, is a visual artist at the cross-section of biology and design. With her on going project, Interwoven, she is rethinking the production of a textile in a more sustainable way.

> "The evolution in the role of technology has brought a cathartic return to the 'roots' of making".
>
> Paola Antonelli (2012)

Inspired by nature she became fascinated by root systems and created a photographic series of root vases she called 'Nature Studies' (2012). This was the beginning of her contemplation into the domestication of root systems. Since 2015 she has been using the hidden processes of plant roots for the formation of her work, by making the invisible, visible. Seeing the roots as if they were yarn to be weaved, the quote above by Paola Antonelli (2012) exemplifies her process as she manipulates the root structure to create a textile.

Potential of Interwoven

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 fibres, the material itself weaves. Producing itself through the search of the plant for nutrients and water. Diana mentions this is, "exciting because I never know exactly how the roots develop. They follow my templates but also find their own way". 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 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.

The creation of a new textile brings with it the possibilities of new sensations, thoughts, feelings and behaviours (Karana, et al., 2015). One unique feature of the material is that it can be directly shaped into the final form. However, it is still a material in development and can be further explored with other processes to uncover its potential to shape the structure, and affect material properties at both technical and aesthetic levels (Karana, 2018).

Interwoven has potential to be developed from an artwork towards a novel material concept that is closer to the wider public (both designers and consumers).

Positioning Interwoven

Co-creating with nature and the use of her own self-made production process means it can be considered as a type of DIY practice (Rognoli et al., 2015); Interwoven is positioned between of growing design and digital biofabrication, because templates are digitally designed to control how the roots will behave. While, one the other hand Diana collaborates with the plants roots autonomy.

The positioning of Interwoven uses the model that maps four approaches using biology for design purposes, created by S. Camere and E. 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. See Figure 2 which illustrates these approaches.

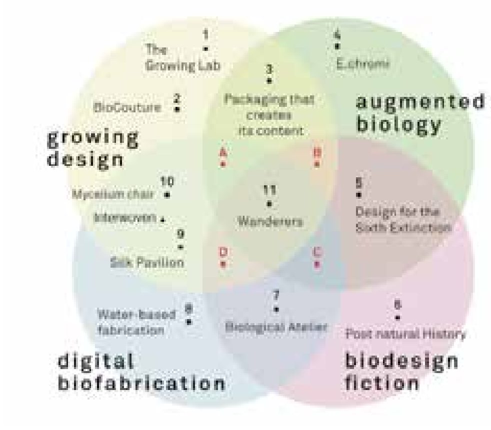


Figure 2. The map of the four approaches using biology for design purposes (Camere and Karana, 2017) The numbers indicate a case mentioned in the original paper.

The next paragraph will introduce the scope of the thesis, problem definition and research questions.

1.3 Project Scope

Diana has an interest in developing Interwoven into a commercial product. She is driven to contribute to "improve our relationship with nature and to turn it into a less destructive and a more integrated model." Particularly to create a more sustainable textile industry for the future.

Introduction

The V&A museum in London invited Diana to create for the exhibition 'Fashioned from Nature', which she called Rootbound #2. The dress is still a concept and the 'Earthy' material is not yet ready to be worn, remaining a speculative piece. However, by collaborating with professionals, such as biologists, engineers and designers she hopes to realise her scientific and technological interests.

Her long term goal is to develop the *"bio-fabricated material into a sustainable and applicable material"* in the textile industry. There is a global demand for responsible textile innovation within the industry. Nature has produced an unimaginable amount of versatile solutions that can serve as technology. Diana sees plant roots as an "overlooked natural resource that offers a clean production process and a sustainable alternative solution to polluting petroleum-based fibres such as acrylic or polyester".

With her vision of Interwoven in mind 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"*. 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.

Problem Definition

In its current state Interwoven is limited in its functional use because of the technical characteristics of the roots being weak. As an individual strand it has very little strength; however once weaved together into a visually appealing matt the over all strength increases. To this end, it still lacks the sufficient durability to behave as a textile. Therefore there is a need to improve the strength as an aspect of durability.

Apart from the technical challenges presented, there are also challenges with peoples perception of new emerging grown materials as they trigger uncertainty in peoples perceptions, and the experiential effects of Interwoven is unknown. For designers, materials play a key role in shaping our experiences and give meaning to the things we use (Hekkert & Karana, 2014).

To summarise the durability of Interwoven needs to be improved and the experiential effects need to be characterised so that both may be utilised towards finding a meaningful application as a textile.

Project Direction

The objective of this project is to study the Interwoven process and explore different methods to improving its strength as a composite, while assessing its technical and experiential properties. Characterised by a DIY approach (Rognoli et al., 2015), tinkering experiments will be executed to provide insights in to how these properties can be modified e.g. changing environmental growth conditions. The project will use the Material Driven Design method (MDD) (Karana, 2015), for the research.

The final aim of the project is to create a material demonstrator to illustrate the quality of the interaction and its experiential characteristics in a final form.

1.4 Methodology

The basis of this graduation project is the material development of Interwoven, which follows the Material Driven Design (MDD) method (Karana et al., 2015). Starting with Interwoven as a new material.

Material Driven Design (MDD)

Grounded on the notion of Materials Experience (Karana, 2009), the MDD method combines practical experimentation, user studies and envisioning. Starting with a material proposal and ending with a product and/or further developed material concept. The method consists of four stages that provide a framework to the research and development of a material; (1) Understanding the material, (2) Material Experience Vision, (3) Material Experience Patterns and (4) Designing Material/Product concepts (figure 3).

The first phase (1) focusses on understanding the material in its broadest sense. It addresses the origin of the material, its production process and explores the material properties through extensive tinkering. Technical tests and user studies help to define the technical and experiential characteristics. A material benchmark functions as a bridge between the first two phases as it gives insights in the opportunities of the material. These opportunities support the formulation of the Material Experience Vision, the second phase of the method (2). The vision represents the 'design goal' of the project and helps to translate the material qualities into a product. Here both technical and experiential qualities are taken into account.

The third step (3) translates the abstract experience qualities (e.g. natural, honest and nostalgic into more tangible material patterns. Here, the Meanings of Materials (MoM) Tool is one way to achieve valuable input on how people associate material patterns with certain meanings (Karana et al., 2009). In the final step (4) the vision steers the concept development to ensure an outcome that emphasizes the qualities of the material. The embodiment of the material in a product allows to validate the concept.

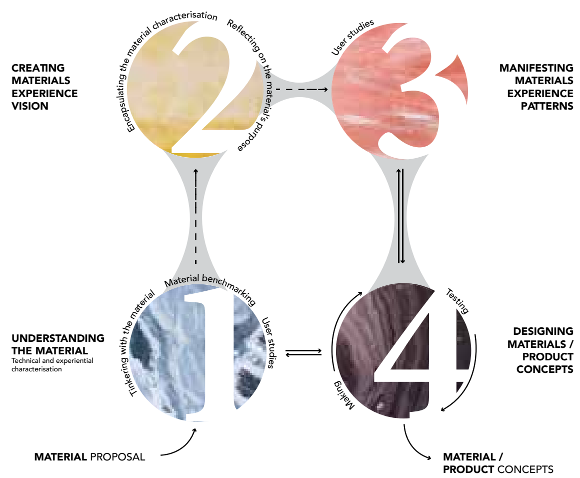


Figure 3. Material Driven Method (Karana et al., 2015).

1.5 Research Questions

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

'How can Interwoven be strengthened towards being a durable textile comparable to other natural fibre textiles?

As a desired requirement Diana wishes that the strength be improved while keeping the **delicate** quality of the root system. Figure 4 below illustrates this contrasting dilemma as an extension of the project direction.

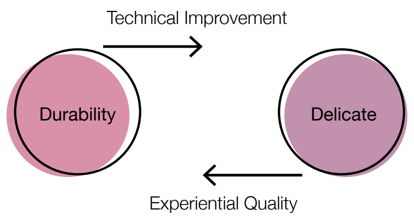


Figure 4. Illustration of dilemma for project direction.

The main research question is divided into smaller parts:

Interwoven
1. What are roots?
2. What is the Interwoven process?
3. How can properties be modified?
4. What are the experiential properties of the material?
a. What are unique sensorial qualities and which are the most and least pleasing?
b. Is the material associated with any other material?
c. Does the material evoke any meanings?
d. Does the material elicit any emotions?
e. How do people interact/behave with the material?
5. What are the technical properties?

Literature Review
1. How to enhance the durability of Interwoven?
2. What kind material experience' are to be expected from Interwoven?

Interwoven
1. What are the experiential properties of the developed material?
2. What are the technical properties?
a. How do these properties change when the ingredients vary?
b. What are the most convenient manufacturing processes?
c. What are the technical constraints and opportunities?
3. How can users perceive Interwoven to be a delicate yet durable material?
4. What experiential qualities are characteristic of delicate and durable materials?
5. What patterns are perceived as delicate and durable?

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

Material Development
1. Which material samples are essential for the design vision?
2. What are their characteristics?
4. Which characteristics are necessary to evoke a certain meaning , emotion or behaviour?
5. Which technical characteristics are necessary to evoke a certain meaning, emotion or behaviour?

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

Image: Picture of back of dress designed and made by Diana Scherer - Rootbound 2

1.6 Thesis Structure

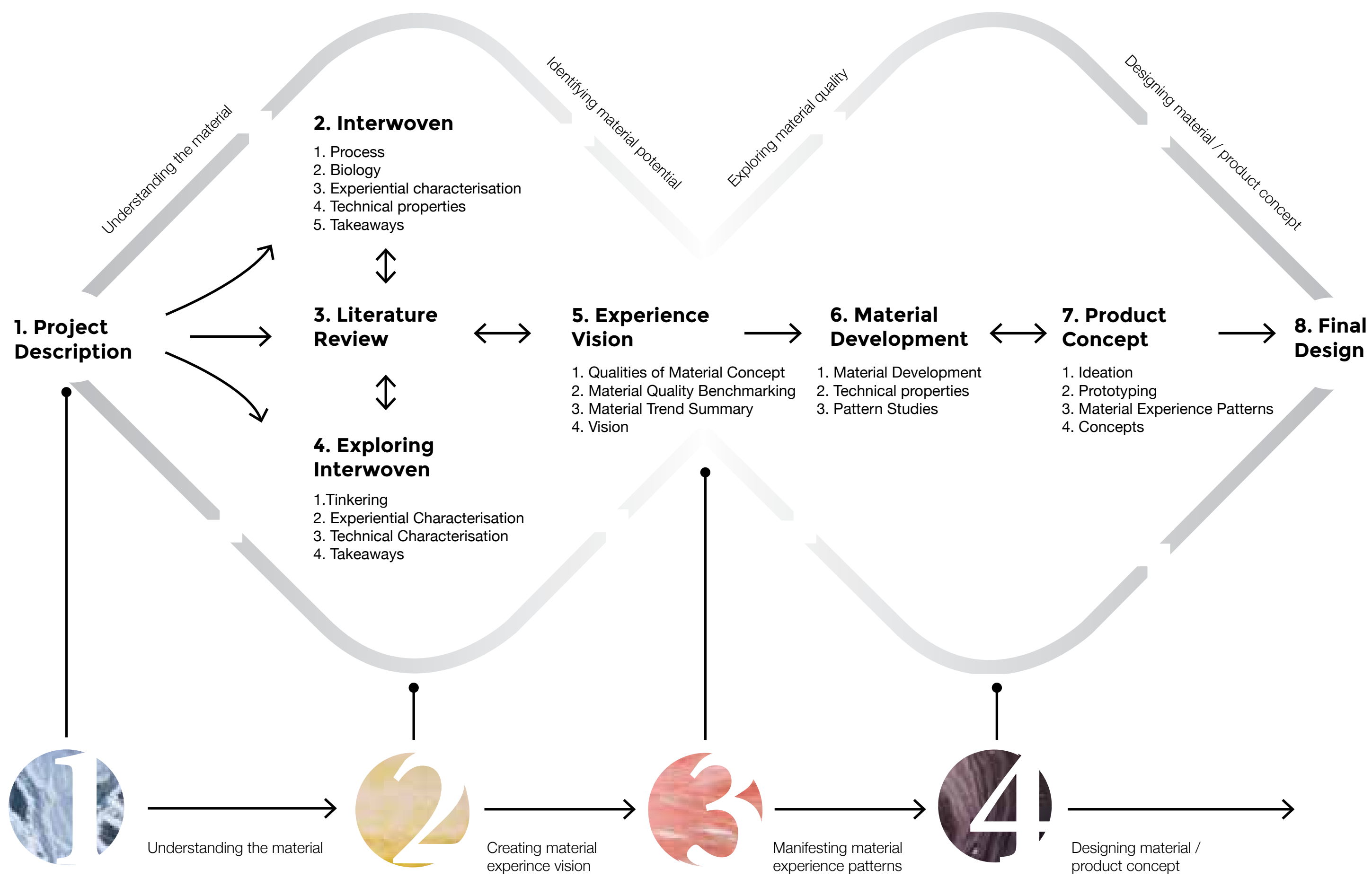


Figure 5. Illustration of structure of thesis indicating parts of the MDD process

2

Interwoven

This chapter introduces the making process, the biology of the root structure, the technical boundaries and experiential characteristics of Interwoven.

2.1 Production Process

In an interview with Diana Scherer practical insights into the growing conditions, ingredients and activities required for the production process, helped create a visual diagram on how the material is fabricated as depicted in Figure 6.

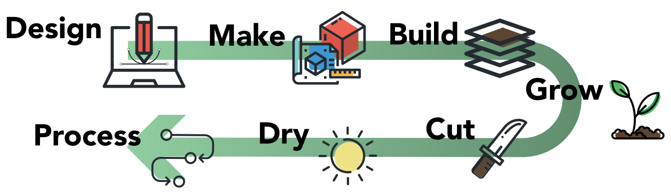


Figure 6. Illustration of production process steps

Seven Step Process

The project is under an NDA agreement, therefore aspects of the production process have not been disclosed in the report. However to summarize, a mould is designed and placed beneath the soil, after which oat seeds and water is added. To simulate daylight hours, artificial pink (red & blue) LED growing light used (figure 7). A timer must be used to simulate the daylight hours and water must be provided regularly to the soil.

Once the germinated oat seeds have been planted their fibrous root system will grow through the soil in its search for nutrients. They burrow through the soil into the subterranean moulds (figure 8) and interweave together into a single material. The process takes 10 days under pink artificial light, before harvesting the material. Although this is shorter in summer months. See figure 9. The root textile is then cut from the structure and left to dry on one of the grids.

Figure 7. Image of pink light used in Diana's studio (own picture)

Through an interview with Diana Scherer potential challenges and opportunities have been identified for development. These are clustered these into themes, which are:

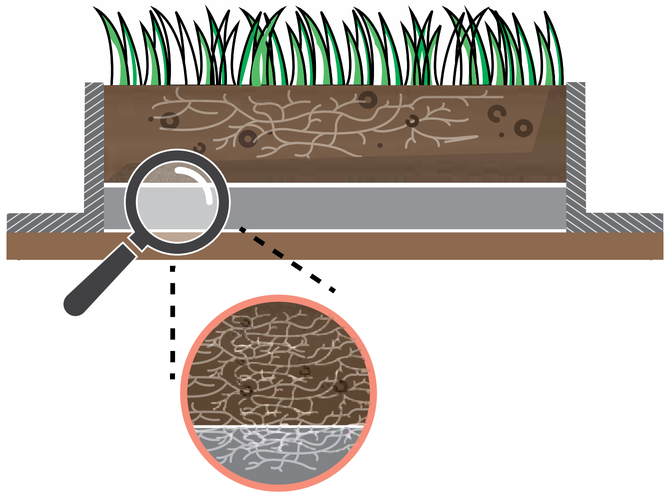


Figure 8. Illustration of roots journey seeking nutrients

(1) Durability, strength and conservation; Interwoven is delicate in its nature, which is not necessarily a disadvantage but could be more functionally applicable if its strength and toughness was enhanced, while still enabling it to be a biodegradable material.

(2) Pattern Development; the patterns will have an effect on the technical and experiential characteristics of the material. It can both support mechanical strength while also being aesthetically pleasing.

(3) Template Development; a challenge exists in designing the template to be more sustainable while also still being fit for the root growth.

(4) A responsible dyeing process; currently the colour is like 'dry sea grass' and so there potential to find ways to add colour in a natural process.

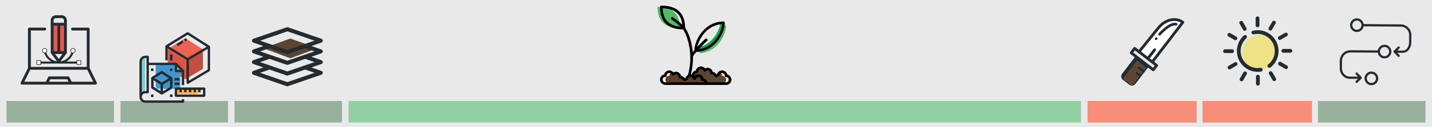


Figure 9. Illustration of time it takes for process

2.2 Technical Properties

As Interwoven is in development, the inherent technical properties are unknown. As part of the MDD process, it is required that some technical characterisation is done to discover its constraints and identify possible opportunities for development.

The following questions should be answered:
1. What are the main technical properties?
2. What are the constraints/ opportunities?

Strength and structure are most relevant technical aspects of this investigation. Therefore, a tensile test and microscopic examination have been conducted.

Tensile Test

A tensile test, is one of the most common types of mechanical testing. A tensile test applies tensile (pulling) force to a material and measures the specimen's response to the stress.

Stress applied to a material before it plastically deforms is called yield strength. Before non-uniform deformation is called tensile strength. If the applied stress is less than the yield strength, the material returns to its original shape (Hook's law eapplies) when the stress is removed, remaining within its elastic region, often called elastic stiffness. However if the applied stress exceeds the yield strength, plastic deformation occurs, and the material can no longer return to its original shape once the load is removed. Plastic deformation before fracture is called ductility. See figure 10 for an overview of a typical stress strain graph. *(Source: https:// www.thefabricator.com/article/ metalsmaterials/thedifferences- between-stiffness-and-strength-in-metal)*

For Interwoven the fragility lies in that it breaks easily under a tensile force. What is the yield strength? Does thickness make a difference? A tensile test is needed to quantify it and compare to existing data of a textile like cotton.

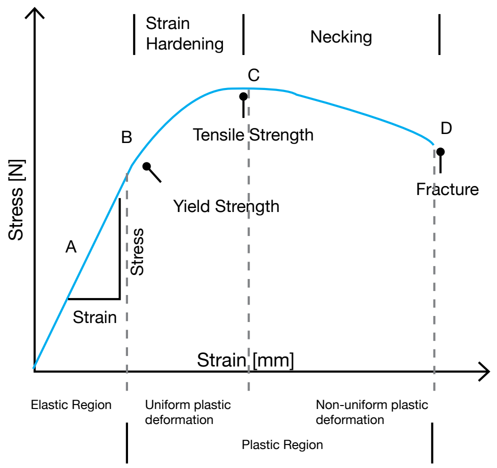


Figure 10. Illustration of stress strain graph

Method

The test takes reference of Standard ASTM D5034- 09 (Standard Test Method for Breaking Strength and Elongation of Textile Fabrics). However, due to the 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 slow change in load. The failure criteria is 12mm of standard travel constant for all samples. The test provides a basic idea of the load bearing ability the current material. Therefore the differences from the standard is accepted.

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 the roots autonomy during growth; however, they reflect the same pattern arrangements. Prior to testing, the samples were accurately measured (weight, length, width and thickness) to ensure a proper comparison. Figure 11 shows the samples.

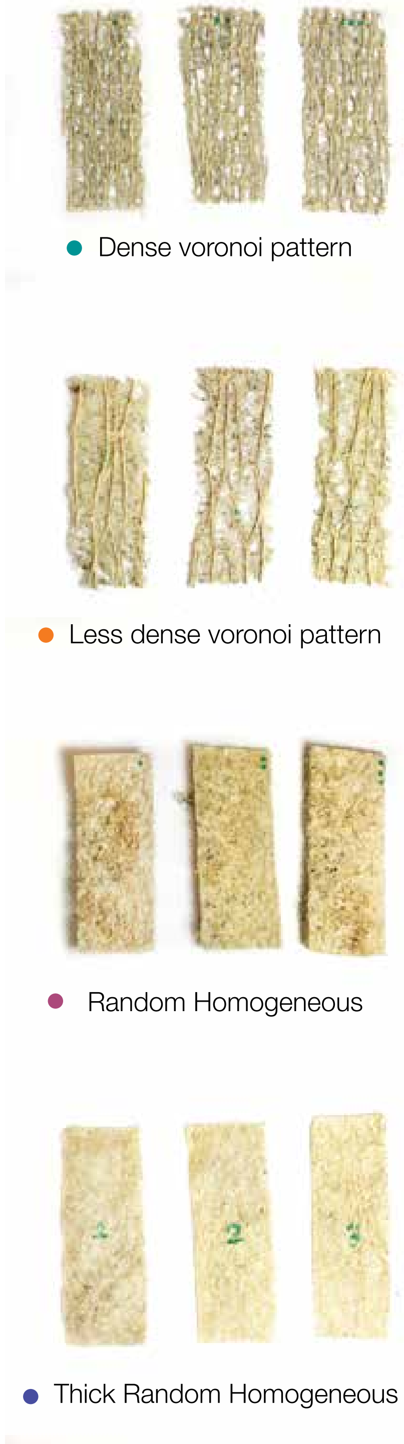


Figure 11. Samples before testing

Results

The units of force are a vector quantity; its units are in Newtons. The results have been converted to megapascals (MPa) for a comparison of internal pressure, defined as one newton per square metre.

The tested specimens show varied tensile strength (figure 12, 13). The test results show that the average tensile strength of a dense (hole size 5mm by 40mm) voronoi pattern is 24.8 N, around 1.2MPa. The less dense voronoi (hole size 10mm by 40mm) pattern is 23.7 N, around 0.4MPa.

100% Cotton, 2017). The current Interwoven samples are much weaker than cotton knitted fabric.

Root density influences strength; the dense voronoi pattern samples are stronger than the less dense voronoi samples, this could be due to a higher density of root pattern contributing to greater resistance to tensile force. The thicker random homogeneous samples have the highest force but when converted to MPa it is weaker than the thinner homogeneous samples. This can be explained when you consider density.

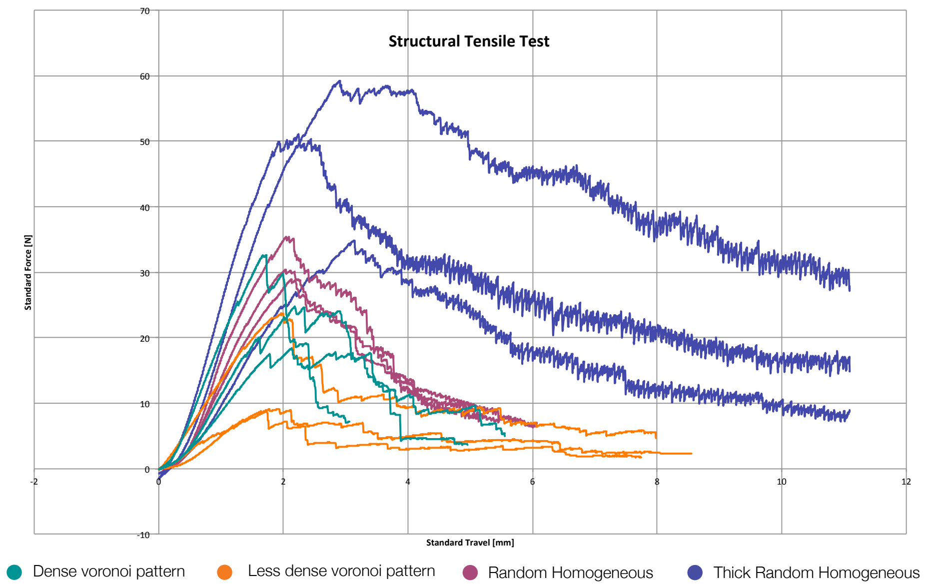


Figure 12. Stress strain curve of tested samples

	Maximum extension	Test speed	Pre-load	Specimen no.	h	b	A_0	Peak detection	Date/Clock time	$L_{E,Ch}$
	mm	mm/min	N		mm	mm	mm²	N		mm
Dense Voronoi 1	3	2	0.1	1	0.86	35	30.1	18.38137817	43658.44994	49.14969
Dense Voronoi 2	3	2	0.1	2	0.78	35	27.3	32.65367508	43658.45515	44.12744
Dense Voronoi 3	3	2	0.1	3	0.77	35	26.95	24.82945061	43658.45834	47.18389
Less Dense Voronoi 1	3	2	0.1	4	0.98	35	34.3	23.70763969	43658.46264	48.05849
Less Dense Voronoi 2	3	2	0.1	5	0.89	35	31.15		43658.468	50.86158
Less Dense Voronoi 3	3	2	0.1	6	1.3	35	45.5		43658.47297	49.8787
RH 1	3	2	0.1	7	0.32	35	11.2	35.49647141	43658.47958	51.24011
RH 2	3	2	0.1	8	0.2	35	7	28.99508286	43658.48359	49.50391
RH 3	3	2	0.1	9	0.38	35	13.3	30.40594673	43658.48744	52.79657
RH thick 1	3	2	0.1	10	2.6	35	91	59.28104782	43658.49176	48.59332
RH thick 2	3	2	0.1	11	2.01	35	70.35	51.02374268	43658.50112	48.0018
RH thick 3	3	2	0.1	12	1.56	35	54.6	34.79828644	43658.50771	48.41708

Figure 13. Results from tensile test on Interwoven samples

The random homogeneous pattern is around 35.5 N, around 3.2MPa. The thicker random homogeneous sample is 59.3 N around 0.6MPa. To see the stress strain graph for correlated to MPa in the vertical axis, see appendix B.

Discussions

Interwoven has low strength; the average tensile strength of 1×1 rib knitted stitch fabrics made from 100% cotton is 325 N, along its length, (the data is collected from Tensile Properties of 1×1 Rib Knitted Fabrics Made from

The density of the thin samples 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 when measured in units of pressure.

Thick samples are more ductile; the curves are zigzagging after the peak force. This can be explained by localised fracturing of the roots under load. The slow dropping curves, show the ductility is high.

Fibrous Root Hairs

Three samples of Interwoven (figure 14) have been taken under a microscope to investigate its micro-structure. The following images of the samples show three different structures: homogeneous, heterogeneous, and patterned.

They are put under a microscope (4.5X) to see the micro-structure of the root fibres. Currently, between the main strings of root fibres there are root hairs, which grow from the 'region of maturation' for water and nutrient intake (Grierson et al., 2002).

Figure 14. a. Homogeneous, b. heterogeneous and c. patterned sample under microscope (4.5X)

These very fine filaments, are abundant with clear visibility. It is speculated that the fine root hairs bind the main fibres together forming a web that holds the roots.

Figure 14b. A bundle of roots densely intertwined together.

Takeaways

The technical characterisation of the current structure are the fragility and the connectivity of root hairs.

Root hairs support root fibres sticking together and could increase friction between the roots (figure 14b). This increase in friction could contribute to strength, which should be taken into consideration in altering root pattern structures. Pattern structures that are larger in form at a cross-sectional area would have a great number of root hairs, which would facilitate greater strength. In contrast to a smaller cross-section with fine in detailing patterns. Certainly the random homogeneous samples exhibited greater resistance to force when higher in density. This would equate to a greater density of root hairs and more random interconnectedness towards higher strength.

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. Since root density has much more influence on strength than patterns, pattern design will not be the main strategy to increase strength. And since thicker samples exhibit higher ductility, a variable like adding more seeds should be considered. That means that even when some roots break, others can still support the function. Linear pattern structures will be considered for technical testing later.

2.3 Biology

In this section background knowledge of root biology related to mechanisms of control and its architecture will be presented.

Roots

Interwoven adheres to principles of nature, as it is a natural material made from roots. The root is an organ of the plant's body, growing downward into the soil's surface. The primary functions of the roots are to anchor the plant, absorption of water and dissolved minerals, conduction of nutrients to the stem.

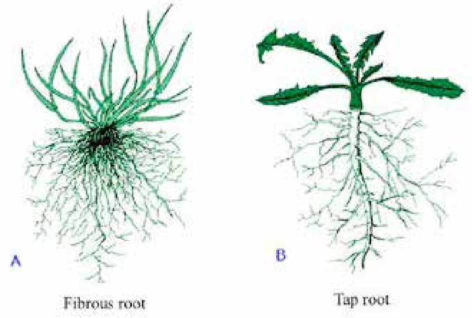


Figure 15. Comparison of fibrous root and tap root

Types of Root System

Figure 15 illustrates 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)*. Interwoven is using oat - a monocot, which has a fibrous root system, causing even distribution of single roots.

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 developed from the stem base. In certain plants, there is a combination of taproots and fibrous roots (Smith & De Smet, 2012).

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).

- 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 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 inter-cellular spaces.

- 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.

a. Epidermis
b. Cortex
c. Endodermis
d. Pericycle
e. Xylem
f. Phloem
g. Pith

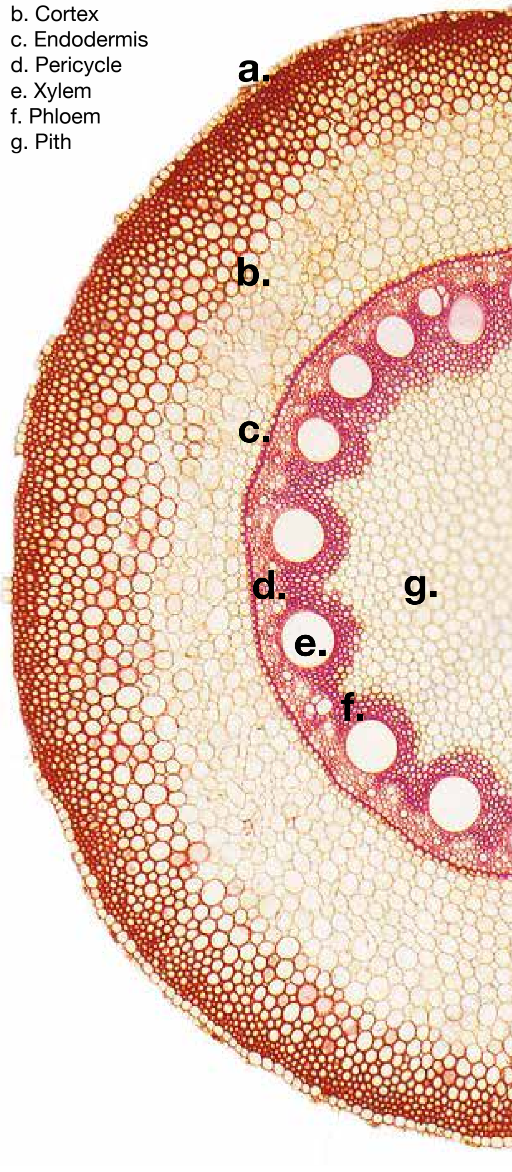


Figure 16. Monocot cross-section (Source: https://www.gettyimages.ae/photos/monocot)

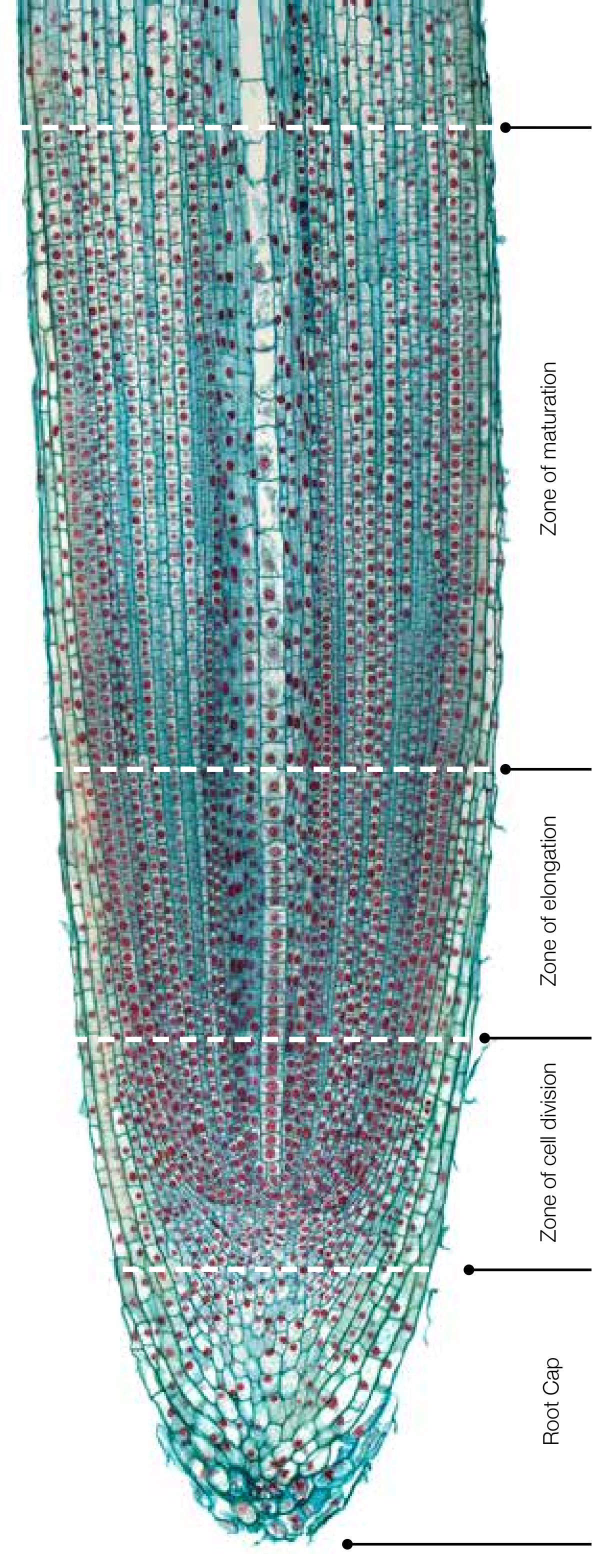


Figure 17. Longitudinal cross-section (source: https://www4.uwsp.edu/biology/courses/botlab/Lab07b.htm)

Figure 18. High resolution picture of root and root hairs.

Root Growth and Development

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

Roots are growing from their ends. The area at the end of the root of actively dividing cells is called apical meristem. As it is easily damaged it requires protection while the root is making its way through the soil. The protective area at the tip of the root is called a root cap (Figure 17). The root cap is a structure exclusive to roots and unlike any other plant structure.

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 17.

All three regions are in approximately the first centimetre of the root tip. During the first phase of cell division, roots are approximately 1 mm in length. The 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.

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 differentiates into specialised cell types. This region is about 2 mm. (Hartnell, 2018 and Caert and Campbell, root anatomy).

Root Perception

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)”.

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

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.

Template: The roots find their way through the soil in a similar way to a person groping through the dark. If they come across some obstacle, they feel their way around it until they come to a point where they can grow again.

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.

Factors that Influence Root Strength

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

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: usually, plants with higher drought tolerance have stronger roots.

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 stimulator’s.

Understanding the organism from biological perspective supports human intervention into the growing process. Cultivation methods play a significant role in further altering root properties.

2.4 Experiential Characterisation

Apart from the technical properties. The experiential effects of Interwoven are unknown. Challenges exist with peoples perception of new emerging grown materials as they often trigger uncertainty. This section covers the experiential characterisation as prescribed by the MDD method.

Designing for Experience

Hekkart (2007) explains that while interacting with a product, a person first comes across the artefact, senses it, perceptually analyses it, compares it with previous experiences, classifies it into a meaningful category, and consequently interprets and appraises it. Materials like products are selected for creating experiences as they convey meanings, gratifying the senses and elicit emotions. A whole series of effects are elicited by the interaction between people and material in a context. When describing materials people refer to technical and sensorial properties, but also according to the meaning they attribute to the material as well as associations and emotions that are evoked.

A hallmark of product designers is designing with awareness of people’s experiences, particularly when offering novel materials as alternatives. The ‘material’ should also elicit meaningful experiences in and beyond its utilitarian assessment and functional aptness. Qualifying the material not only for what it is, but also for what it does, what it expresses to us, what it elicits from us, and what it makes us do (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015). The notion materials experience emphasizes technical and experiential levels, experiential having four levels of experience; namely sensorial, interpretive, affective and performative. These are 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).

These levels articulate a functional understanding of materials experience, categorizing different experiential qualities that can be elicited by materials.

Material Experience

A material carries five layers of information: technical, sensorial, interpretive, affective and performative (Karana et al., 2015). The experience of a material is divided into four layers, described below:

Sensorial level: The technical characteristics of the material are experienced with the senses through touch, vision, smell, sound and taste.

Interpretive level: How we interpret and judge materials. The meanings we ascribe after the initial sensorial encounter; for example modern, traditional, elegant.

Affective level: How we feel about the qualities of the material on an emotion level; for example fascinated, surprised, disgusted.

Performative level: How the material affects our actions; for example touching, picking, stroking.

Introduction

This section focusses on the experiential characterisation of the material. The material experience on all levels was investigated of an Interwoven sample.

The Material Driven Design method (Karana et al, 2015) presents a list of questions that guides the understanding of the four experiential layers:

- What are the unique sensorial qualities and which are the most and least pleasing?
- Is the material associated with any other materials?
- Does the material evoke any meanings?
- Does the material elicit any emotions?
- How do people interact/behave with the material?

To answer these questions, the experiential characterization study was conducted with 3 participants separately.

Aim: *Uncover interrelationships between the material properties and the experiential levels. Identify which material properties are associated with a particular meaning should be kept or modified for future development.*

Set Up

To conduct an experiential characterisation, a study was set-up to provide qualitative data on the perceptions, opinions, beliefs and attitudes towards Interwoven. This addressed each experiential layer of the material. However, people often experience difficulty expressing and verbalising their experiences with materials: How does it make you feel? What associations does it evoke? These can be challenging questions to answer without knowledgeable vocabulary. To facilitate these questions the **Ma2E4** tool kit was used.

Participants

Three participants from the Industrial Design faculty of Delft University of Technology participated. Their respective disciplines were: Integrated Product Design, Strategic Product Design, and Design for Interaction. None of the participants were familiar or aware of the material.

The Sample

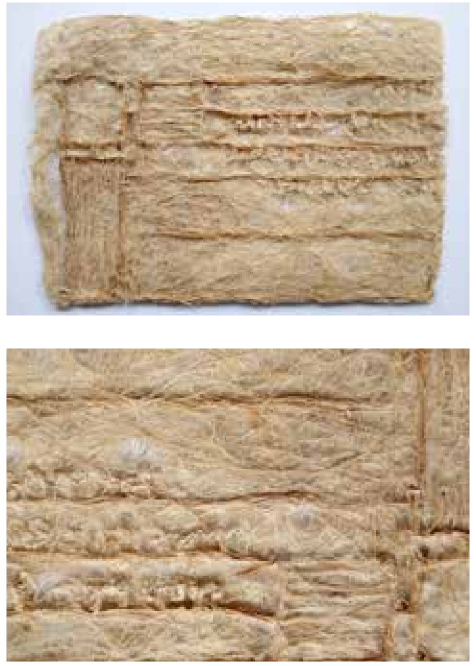


Figure 19. Interwoven sample grown by Diana Scherer

Method

To determine the material experience on all levels the Ma2E4 tool kit is used, developed by Karana and Camere (n.d.). This tool kit provides a structured method to create understanding of how a material is experienced on the four levels of experience.

To streamline the process a booklet inspired by the Ma2E4 tool kit (See appendix A) was designed in stages that followed the structure of the tool kit, the structure is as follows:

1. Performative qualities: Participants are asked to spend 5 minutes exploring the material. The designer considers the following questions: *How do they move the material?, How do they touch the material? How do they hold the material?* Next to each question is a multiple choice of answers that the designer fills out with notes.

2. Sensorial qualities: The participants are asked to rate the material according to the provided sensorial scale (Karana, 2009).

3. Affective qualities: An affective vocabulary is provided, the participants are asked to familiarise themselves with them, both negative and positive. The list of emotions are based on Desmets 2012 positive emotion typology and vice-versa for the negative emotion typology. *(Retrieved from: http://emotiontypology.com.)* The participants are asked to select a minimum of 3 emotions, place them on the graph according to the axis provided and talk aloud their reasoning. The designer records their remarks.

4. Interpretive qualities: Another list of words are provided to the participants, this time including sets of meanings that were found as the most relevant and frequently used descriptive items for materials (Karana, 2009). Including the words delicate and durable as these are key meanings for the project (see appendix B) asked to select 3 or more meanings and explain why. From the defined meanings the facilitator provides corresponding pictures that were generated by the designer, the participants are asked to select one or two pictures that describe their chosen meaning (see appendix B).

5. Final Reflection: In order to deepen the conversation the facilitator asks 3 questions, *What is the most pleasant quality?, What is the most disturbing quality?, What is the most unique quality?* The facilitator takes notes of the responses and probes to know more with questions like, *Why do you think the material is aggressive?*

Results

The analysis of the data is qualitative, due to the limited number of participants. The following pages show the results and are then discussed in the order of the method. Emotions are grouped according to positive emotion typologies by Desmet (2012). To uncover individual appraisals, the seven themes of Karana (2009) were used to categorise, with the addition of one more systemic theme introduced by Bahrudin. F, 2018.

Below are the eight themes used for the analysis and discussion.

1. Use: Establishing the appropriateness of the materials in general use and properties to applications. E.g. hold heavy stuff, for guys or girls, for an active person.

2.Manufacturing: Expressing applied production and treatment. E.g. layers of material, set in resin.

3. Technical: Verification of performance and functional integrity. E.g. elastic, flexible, strong, resistant to tear.

4. Sensorial: Relating directly to the aesthetics of the material, usually centred on visual and tactile aspects. E.g. texture, hardness, softness, smooth.

5. Emotional: Response elicited from interaction with a material. E.g. Surprise, amusement, worry.

6. Interpretive or expressive semantic: Focused on making meaning from aesthetics, technical and use aspects of a material. E.g. durable, warm, playful, natural, nostalgic.

7. Associative: Expression of comparable materials or experiences. E.g. paper like, rubber like, leather like, old temple.

(Karana, 2009)

8. Systemic: Perceptual analysis of positive or negative aspects of a material within its whole life cycle, including its origin, production, use, and end of life. E.g. biodegradable, bio-based, organic, decomposable.

(Bahrudin et al., 2018)

To view the results clustered together please see appendix C.

Participants:

Age 23 - 26 / Background: Design masters students / Italian, Spanish, Dutch

(1) Performative

Performative Level

The interactions are: pressing, rubbing, pulling, caressing, folding, lifting and looking through, bending, smelling, stroking and squeezing. The most common interactions are rubbing, caressing, folding, bending and stroking. **The quality of stroking and rubbing are careful and delicate but with assurance, some participants explored the material by rubbing it on different parts of their body like their forearm and cheek. Bending and folding are performed with tentativeness and in small exploratory stages.**

Discussion

The stroking and rubbing is encouraged by the rough fibrousness of the material as well by the root hairs that are random and interconnected.*"You could spend a long time exploring the roots".* All the participants were curious about its ability to be pulled or folded to test its strength but also they re-framed from aggressive actions out of fear of breaking it as they considered is as delicate or fragile, *"I worry I will pull it apart and destroy it, I'm careful because its delicate"*.

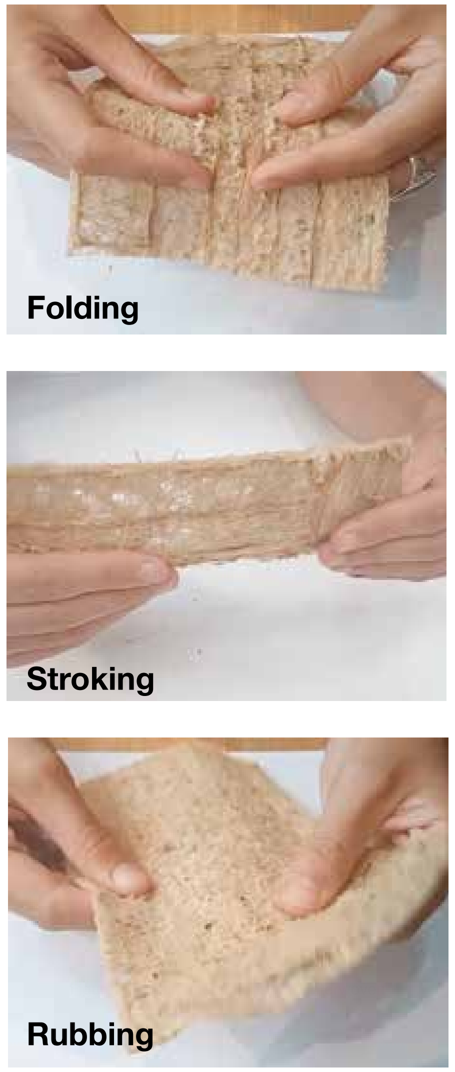
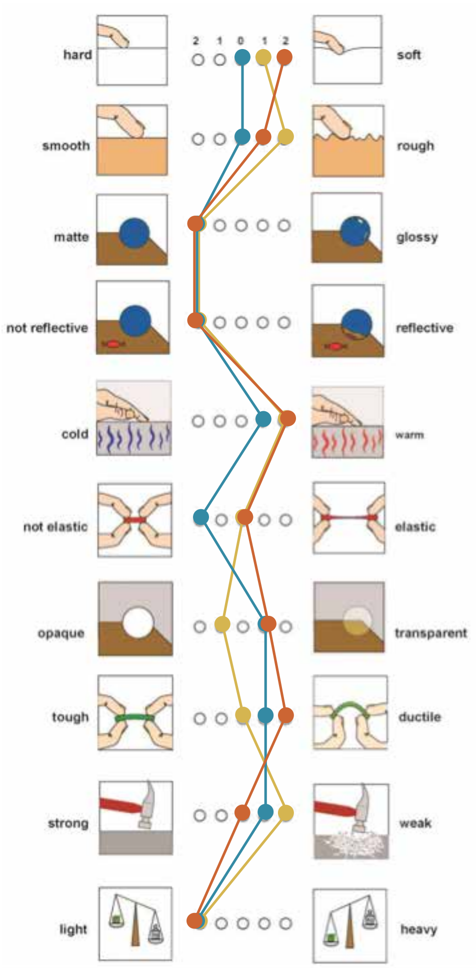


Figure 20. Users interactions with Interwoven.

(2) Sensorial



Sensorial Level

The material is considered to be mostly **soft, rough, matte, not reflective, warm, not elastic, opaque but transparent, ductile, mostly weak but slightly strong, light, fibrous and irregular.**

Discussion

It was considered soft when held in the hands or rubbed on the skin of the arm, this is because of the root hairs and the back side of the material being fluffy and the inter-weaved roots having some compression. In this sense they considered it to be slightly strong in compression. The discrepancy in transparency and opaque is that the fibres themselves are not transparent but the overall material has a heterogeneous quality that allows light to pass through and some holes to exist. This was appraised as the most pleasing quality because the heterogeneousness or irregular fibrousness allows the viewer to keep exploring the roots, *"like a Hieronymus Bosch painting which has lots to explore".*

Affective Level

The emotions mentioned are visualised on the map. Overall the material triggers **respect, kindness, worship, surprise, fascination, satisfaction, shame and worry.**

Discussion

The emotions evoked are in general mostly positive, of which respect was mentioned twice in regards to *"respect to nature"* in terms of her ability to create, *"seems like mother nature did this"*, which is a systemic description of the participants considering the origin of the material.

Technical descriptions were used to describe shame because it was in verification to the performance of the material, *"when I broke it I felt shame because its delicate and should be respected"*. On the other hand its delicate nature elicited a feeling of kindness due to the associations to mother nature. Interestingly the other unpleasant emotion of shame were described in terms of expressive semantics as they focused on making meaning from the aesthetics. With the material being described as puristic, truthful and associated *"close to God"*. Expressing a strong statement about a persons values, but described by the participant as *"giving too little faculties to your self"* and to *"chill and live comfortable".*

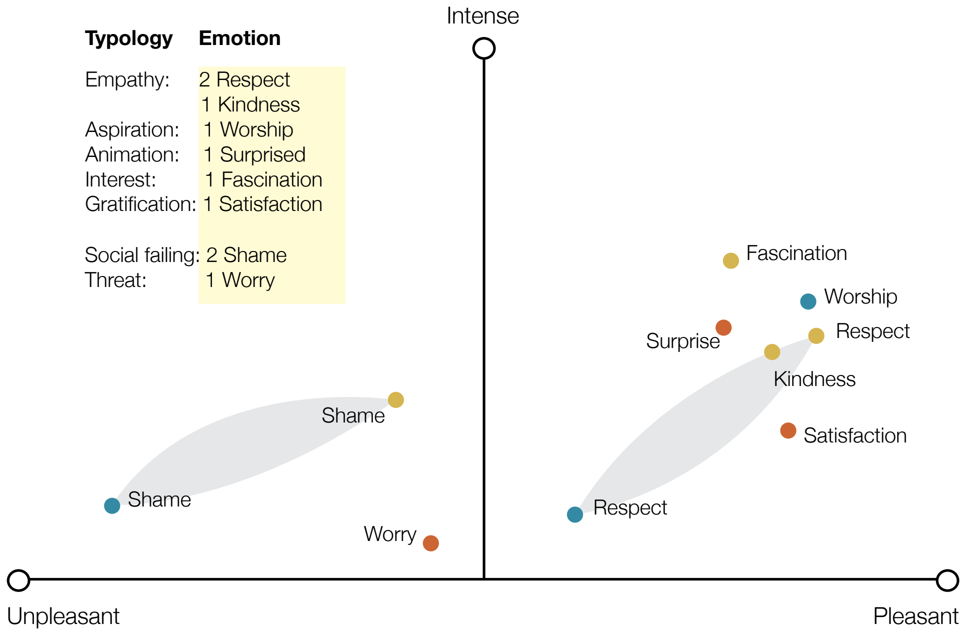
Similarly another participant said that the material *"shows that I care about the environment and speaks to my values, what I stand for"*. Worship was also mentioned because it was assessed as being an *"ecological material"* with associations of being "close to Earth" because of its known origins being interpreted as honest and sober, *"anti-frivolous, like stoicism"*. These indicate that the origin of the material plays a large role in the material appraisal.

Surprise, satisfaction and fascination were described using intrinsic aspects of the material which were centred around the tactile and visual senses. Surprise being from an incongruity of senses, *"it doesn't feel how I expect it to feel"* The expectation of touch was different to the perceived sense, leading to surprise. The satisfaction was a longer lasting emotion because *"its an interesting object to touch"*. The participant also added that if it had felt how they expected to, the satisfaction wouldn't have lasted very long. Fascination was elicited because they could see the roots and observe the growth.

Finally, worry was evoked in relation to its technical ability and uncertainty of its functional integrity. *"I worry I'll pull it apart because it is delicate"*.

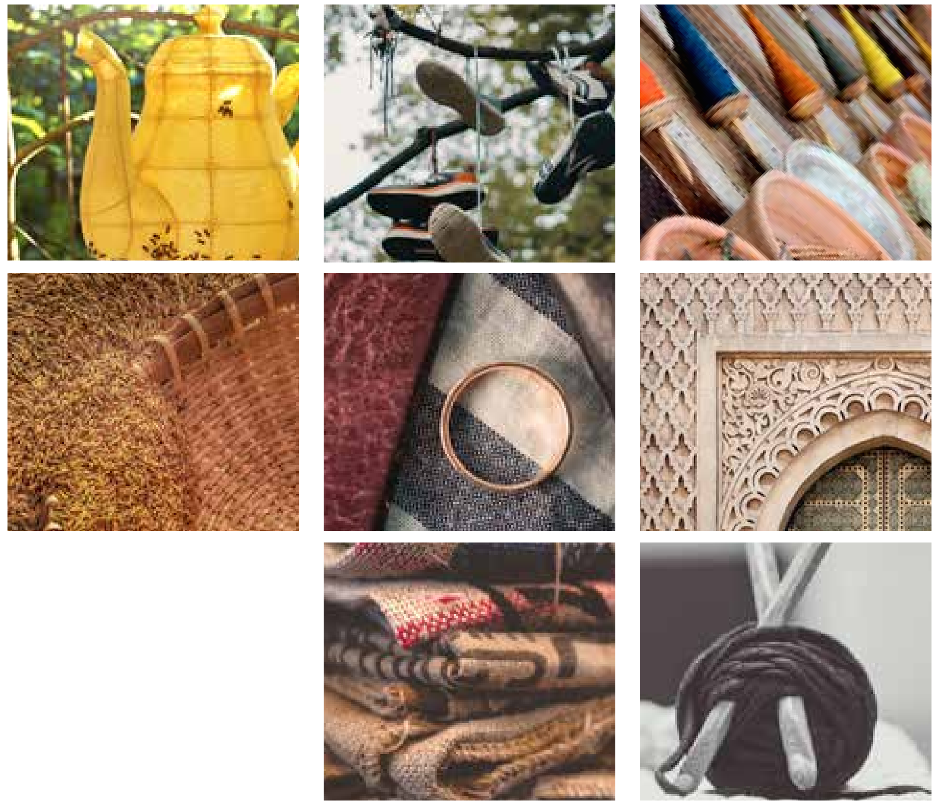
(3) Affective

Typology	Emotion
Empathy:	2 Respect 1 Kindness
Aspiration:	1 Worship
Animation:	1 Surprised
Interest:	1 Fascination
Gratification:	1 Satisfaction
Social failing:	2 Shame
Threat:	1 Worry



(4) Interpretive

Natural n=2/3 **Nostalgic n=2/3** **Handcraft n=2/3**



Other meanings: Sober, delicate, feminine

Interpretive Level

Interpretations evoked by Interwoven are dominated by the meanings **natural, nostalgic and handcraft** with additional interpretations of **sober, delicate and feminine.**

Discussion

Natural interpretations are to do with the biography of the material as participants mentioned the process of growing and the fact that *"there are these roots"*, which are visible to see their growth path. The heterogeneous effect of the roots elicited a handcraft interpretation, *"looks human made"* because its imperfect but this was interrelated to interpretations of nostalgia on a "humanity level" and as *"the basis of humanity"* in reference to the beginning of early civilisation development, with further associations to a *"rough burlap sack"*, which is still common to see in many rural villages in development in the Eastern sub continent .

Associations

"Reminds me of mother nature"

"Monk Material, like a worshipper, close to Earth"

"Its like a burlap sack"

"I imagine it being a lamp shade"

"Manipulating nature is like foot binding children"

"The pattern talks about the culture behind it, like Arabic mosques"

"Could be blinds"

"Close to God"

"Close to Earth"

Final Reflections

In the final reflection participants considered the heterogeneous and irregular effect of the roots being the most pleasant quality as each area is different, with a lot to constantly explore and touch. It was appreciated that this is *"made by mother nature"* but looks like it has been handcrafted. Additionally, the most unique quality is that its a natural material, in regards to its origins and that the roots can be manipulated into different patterns, which could be used to elicit connection to a cultural reference and enhance the handcraft effect, *"the patterns talk about the culture behind it"*. Alternatively this was counterbalanced as one participant felt empathy for the roots, *"I feel bad for the roots"* and was associated to *"foot binding children"*.

To finish the most disturbing quality is the sensorial effect, in that the soil was visible and also rubbed off on their hands as residue. Some participants thought it was a fungus, which has negative connotations and should be avoided in future designs. Although it didn't elicit a strong reaction as they were more worried about the functional performance of the material in use in regards to its strength.

Main Takeaways

Sensorial

1. Imperfect fascination
The heterogeneous irregular fibres stimulate visual and tactile exploration of the roots and potential patterns.

2. Disturbing dirt
Negative connotations are associated to the appearance of dirt and fungus in the material.

Performative

3. Delicate performance
Its delicate root architecture evokes kindness but also creates uncertainty in its technical performance.

4. Symbolic connection
Patterns can be used to enhance the personal connection to the material with reference to a pattern from a specific culture or patterns universal to all of us.

Interpretive

5. Mother natures handcraft
Made by Mother Nature but looks handcraft. Fibrousness and roughness elicits natural, handcraft interpretation.

6. Surprising satisfaction
Emotional surprise from an incongruity of senses, leads to longer lasting satisfaction.

Affective

7. Roots evoke connection
The origin of the material plays a strong role in positive emotional appraisals and associations of connection to nature.

2.5 Conclusion

Taking the technical properties, biology of the roots and the experiential characterisation into consideration, the following is a summary of the main findings.

Strengthening the Roots
Interwoven is very weak in terms of resistance to tensile force. However, the tensile test showed that higher density and random homogeneous inter-weaved root architecture will be more advantageous for increasing strength. A more dense root structure over a cross-sectional area will have more root hairs. Contributing to the overall strength, due to increase connectivity between the roots. Density can be increased with cultivation means by adding more seeds and limiting the amount of water used during the growing process. This increases growing time and the strength.

Roots Evoke Connection
The origin of Interwoven stimulates positive affective and interpretive appraisals of being connected to nature. The uncertainty in its technical performance is reduced when considered from systemic perspectives. Rather it is appreciated as the dynamic irregular movement of the roots are visible. The ability to manipulate natures ‘craft’ into a desired form can be utilised to symbolically represent a connection to nature. The template pattern designs should consider increasing root connectivity.

Delicate performance
The origin of the material evoked delicate interactions with the material as participants were careful not to break it. Exposing the root architecture can evoke a delicate quality of interaction. Therefore strength should be improved while exposing the heterogeneous and random roots.

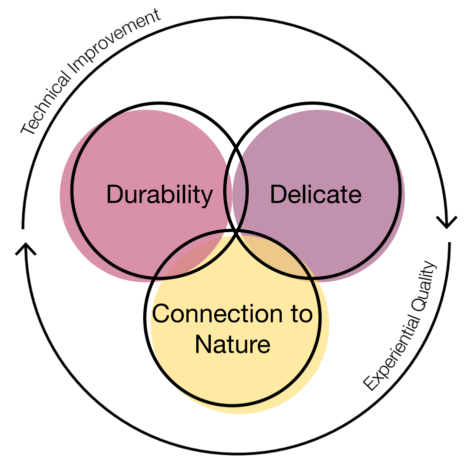


Figure 21. Illustration of developed design direction

As a personal motivation it desired that the **connection to nature** be kept as a requirement for the material experience of Interwoven. This is because the designer believes strongly that we have collectively forgotten our connection to nature with modern society. Hedonistic self indulgence of materials has led humanity to take from and shape nature for economical benefit. Without considering the true cost to nature. Interwoven however, is a collaboration with **nature as the main crafter.** If users can appreciate the strength of nature and feel connected perhaps they will change their behaviour towards it.

3

Literature Review

This chapter covers bio-composites and bioplastics. Followed by a review of expected material experiences, of sustainability, naturalness, imperfection and the aesthetic preference of patterns.

3.1 Bio-composites

This review is a condensed summary of the most relevant information towards answering the following questions:

1. How to enhance the durability of Interwoven?

The role of product design in contributing to cleaner systems of production is evident as an increasing number of alternative and sustainable materials are being explored for production. The use of natural fibres in composites is one such strategy. Here an overview of bio-composites, natural fibres and bio-based polymers is presented.

Introduction

A composite material is produced from at least two different materials that together have other, unique and usually enhanced material performances and properties (Taekema, 2011). Bio-composites contain at least one bio-based component, the term bio-composite is used here to denote fibre-reinforced polymer composite materials where the fibres and/or matrix are bio-based. The advantage of bio-composites over conventional materials is that they provide an alternative for fossil resourced materials, ultimately reducing CO2 (Rognoli, Salvia & Levi, 2011).

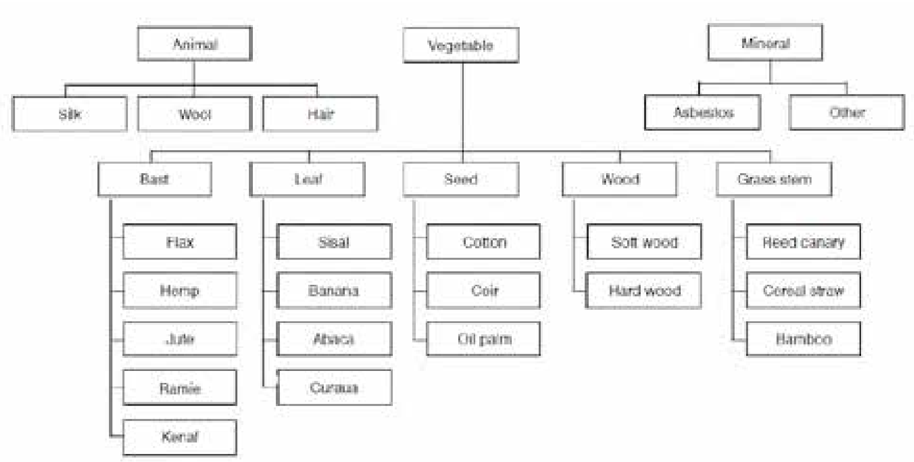


Figure 22. Type of natural fibres (Robert Q et al., 2014)

Types of natural fibres

A wide range of natural fibres exist and they can be classified into three main groups: plant, animal and mineral (Figure 22). The most interesting fibres for composite reinforcements are from plants, in particular bast, leaf and wood fibres. Bast fibres, such as flax, hemp, jute and kenaf, are taken from the stem of the plant and are most commonly used as reinforcements because they have the longest length and highest strength and stiffness. These types of plant fibres are composed principally of a combination of cellulose, hemicellulose and lignin. From an environmental perspective, these fibres are biodegradable, recyclable and are 'carbon positive' since they absorb more carbon dioxide than they release (Robert Q et al., 2014).

Factors Effecting composites

1. Properties of natural fibres.
2. Surface interaction between fibres and matrix.
3. Form of fibres (Continuous or discontinuous)
4. The orientation or arrangement of the fibres (aligned or random)
5. Amount of natural fibre used.

Fibre Arrangement

To achieve strength and stiffness in a composite, the *reinforcement fibres should be continuous and aligned in the direction of the applied load.* Aligned fibres such as those in woven or multi-axial fabrics offer improved mechanical properties over short, randomly oriented fibres like those in non-woven mats (Arnold, Eetal., 2007). Additionally, properties of composites can be tailored to meet different force loading requirements, by stacking the layers. See figure 23 below.

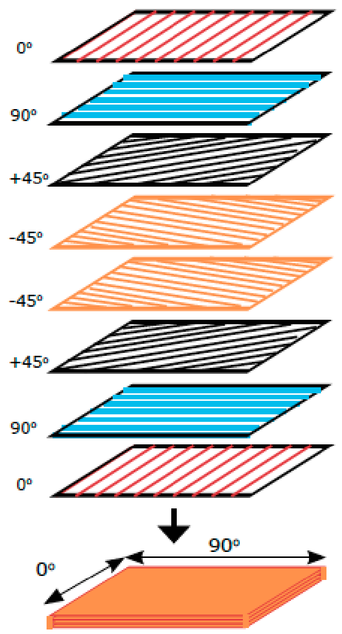


Figure 23. Illustration of stacking fibres in layer (source: Natural fibre composites for designer, 2015)

1. Arnold, E., Weager, B., Bishop, G.,
"Development of High Performance Bio-Derived Composite Materials", Composites Innovation, Barcelona, Spain, 4-5 October 2007
2. Mohanty, A.K., Misra, M., Drzal, L.T. (Eds.), "Natural Fibres, Biopolymers, and Biocomposites",
CRC Taylor & Francis, 2005
3. Yates, M., Barlow, C., "Life cycle assessments of biodegradable, commercial biopolymers — A critical review", Resources, Conservation and Recycling, Volume 78, September 2013, Pages 54–66
4. Robert Quarshie., Joe Carruthers, "technology overview, biocomposites", knowledge transfer network, 2014

Bioplastics and Biobased Polymers

Biopolymers are naturally occurring materials and bioplastics are man made material , usually re-rived from feedstock. Bioplastics can be derived from biomass, synthesized from bio-derived monomers or produced by micro-organisms. Figure 24 gives an overview.

In a composite the matrix surrounds and supports the natural fibres by maintaining their position. Typically the matrix is higher in volume percentage than the fibre material. The reasons to combine natural fibres and polymer matrix' are:
1. Protection: A matrix is added to protect fibres from damage.
2. Distribute load: If one fibre breaks then the load can be transferred to surrounding fibres through the matrix.
3. Binding: The polymer is used to provide shape and structural stability.

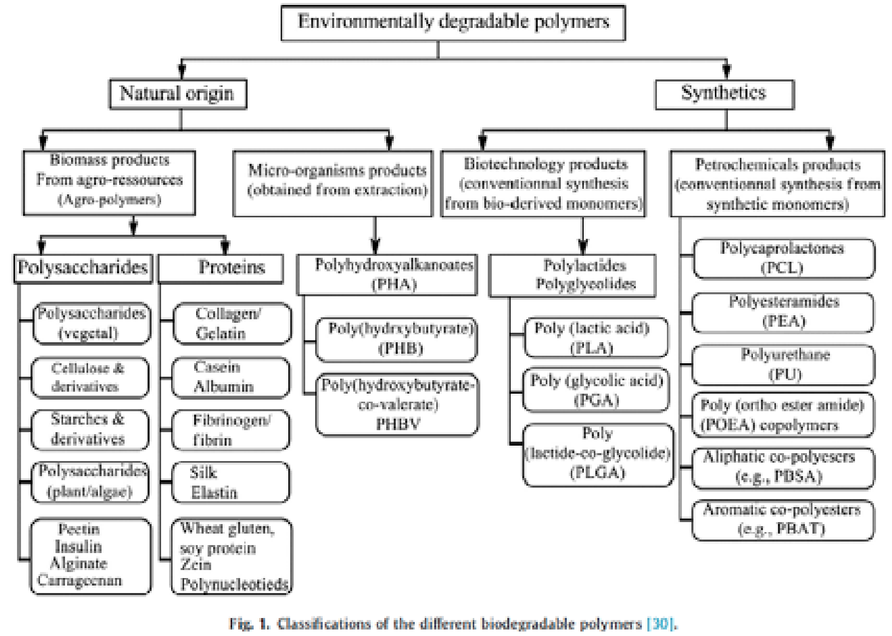


Figure 24. Classification of different biodegradable polymers. (source: T. Gurunathan et al., 2015)

Biodegradable

It is important to note the distinction between bio-based and biodegradable polymers because not all bio-based polymers are biodegradable and vice versa. Bio-based polymers are polymeric materials which are made from natural, renewable raw materials, whereas biodegradable polymers are those which can be broken down by microorganisms at end of life (Robert Q et al., 2014). There are also significant differences between degradable, bio-degradable and compostable polymers.

Degradable polymers break down into smaller molecules or fragments through chemical reactions initiated by, for example, heat or UV light. Biodegradable polymers can be converted by naturally occurring microorganisms (microbes such as bacteria, fungi or algae) into biomass, carbon dioxide and water and, therefore, are considered to be more environmentally friendly than degradable polymers (Yates, 2013).

For a polymer to be considered compostable, it should break down at the same rate as other compostable materials such as paper and should result in a compost like material which supports plant life and does not contain toxins (Robert Q et al., 2014).

Thermoplastic bio-based polymers

Below is a list of some existing thermoplastic bio-based polmyers.

Starch
Starch from corn, rice, wheat or potatoes can be used to produce polymers and is an inexpensive and abundant base material [Mohanty et al., 2005].

Cellulose
Plant cellulose can be used to make cellulosic plastics by using the acetylation process. Examples include cellulose acetate (CA),

PLA and PHA
Polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are biodegradable polyesters which are made from bio-based sources. PLA is a versatile bio-based polymer produced through the fermentation of sugars or the conversion of starch, for example from corn. Additionally non-woven natural fibre mats can be produced with PLA.

Lignin
Lignin is a natural matrix material which binds the strong and stiff cellulose units together in, for example, natural wood. Once separated, it can be chemically modified or blended to produce a thermoplastic-type polymer which can be heated and processed like synthetic thermoplastics (Robert Q et al., 2014).

DIY Bioplastics

DIY material development (Rognoli et al., 2015) is relatively new, there exists a number of DIY based projects in literature (H. Zuberi and M. Bengisu, 2019; M. Riaudo, 2014; V. B´atori et al., 2017); that provide recipes and instructions of self production. Particularly with making bioplastics from pectin, agar and alginate. It is unknown how they will perform in a bio-composite.

3.2 Material Experiences

This review is a condensed summary of the most relevant information towards answering the following questions:

2. What kind material experience' are to be expected from Interwoven?

Over the last decade, we observe an ever-increasing interest in creating and designing with new materials (Karana et al., 2016; Rognoli et al., 2015; Wilkes et al., 2015). The emergence of new materials, such as Interwoven offers opportunity for achieving new material experiences in design. Connected to the idea of Product Experience (Desmet & Hekkert, 2007) the concept of Material experience by Karana is defined as "the experience that people have through and with materials" (Karana, 2009), considering senses, meanings, emotions (Karana, 2009) and performing (Giaccardi and Karana, 2015).

As Interwoven is produced through a self created process and with collaborating with an organism, Interwoven is classified within the increasing category of 'DIY' materials (Rognoli et al., 2015). DIY is derived from a broader concept of emerging material experiences (Karana at al., 2015). DIY materials is defined as "materials created through individual or collective self production practices, often by techniques and processes of the designer's invention. They can be totally new materials, modified, or further developed versions of existing materials" (Rognoli et al., 2015). They have become increasingly popular because of the following reasons: concerns about sustainability, desires for unique material expressions, or an activist reaction to mass production (Ayala-Garcia et al., 2017; Rognoli et al., 2015). The next paragraphs will explore aesthetics and perceptions patterns formed. As Interwoven is a grown organic material, that comes from nature and goes back to nature it is likely to be considered a **natural** and **sustainable** material. Alongside naturalness another aesthetic quality is an emergent theme, called **imperfection** which often includes aesthetics feature of nature that express traces of life, reinforcing emotional linking in time and space (G. Salvia et al., 2010).

Material Kingdoms

DIY materials have been classified as a new class of material categorised into different kingdoms (Ayala-Garcia et al., 2017), called the DIY materials kingdoms. Referring to the source of the ingredients, the five kingdoms are: Kingdom Vegetabile, Kingdom Animale, Kingdom Lapideum, Kingdom Recuperativ, and Kingdom Mumantis.

Uneven texture	Honest	Natural colour in volume
Matte	Rough	Signs of time and use
Textured	Coarse	Subtle colour
Cheap	Freedom of shape	Curly
Common	Non-uniform colouring	Similar colours
Rugged	Breakage	Wrinkled
Warm	Fibrous	Disorganised
Organic	Irregular	Granular
Unique	Unsafe	Crafted
Smelly	Traditional	Natural odor
Expendable	Light	Natural
Informal	Weak	
Handmade	Patina of time	

Figure 25. Aesthetic attributes and qualities of Kingdom Vegetible

Kingdom Vegetabile

Kingdom Vegetabile includes DIY materials with a primary source derived from plants and fungi (Ayala-Garcia etal., 2017), Interwoven falls under this Kingdom. Common characteristics have been identified to all the cases under this Kingdom, including: traceability of the source, as a way to see and recognise traces of the main constituent i.e. roots; imperfection of the surfaces concerning touch and sight perception; unevenness and roughness; the short life attribute as a consequence of their organic sources; traces of decay, flaws and broken edges expressing delicacy and fragility of the material; and the inherent degradability of the material (Ayala-Garcia etal., 2017). A list of aesthetic attributes and qualities are listen below. The aesthetics and qualities of this kingdom highlight the some potential attributes to be evoked by Interwoven, which is at odds with current material design practices which are very much concerned with homogeneity and precision.

Sustainable Materials

Our resource-consuming society, takes out too much and too quickly from Earth for it to keep self-renewing (Chapman, 2005). Since consumers became aware of these consequences, the use of materials and its relationship with the ecosystem are being re-evaluated (Chapman, 2005). More and more sustainable materials are being commercialized and used for everyday design.

The success of a sustainable material ultimately depends on users' perception. A successful product innovation requires users' appreciation of the product characteristics (Rogers, 1995). Products that serve needs and give meaning to users will survive better in the market (Heskett, 2002).

Perception towards sustainability involves many aspects. For instance, renewable materials are believed to be a better alternative to conventional materials but this depends on the plant material used, the cultivation methods and the land used (Álvarez-Chávez et al., 2012; Hottle et al., 2013; Piemonte & Gironi, 2011). Also users' preconception and world views will set the kind of sustainable issues prioritised (Wilkes, 2014).

On the other hand, the imperfection of the sensorial properties of sustainable materials is retained to look sustainable and delight users. The congruity of visual appearance and sustainability claims has proven to influence users' affective attitude (Magnier & Schoormans, 2015). The unique surface qualities and ingredients become active stimuli to users' cognition and elicit various kind of emotions (F. Bahrudin et al., 2018).

The development of sustainable materials is at its infancy but is expected to expand further as it resonates with the circular economy concept (Bahrudin et al., 2017). Acceptance of sustainable materials is not without challenges. For instance, users intuitively believe that natural materials are healthier and more environmental friendly than synthetic materials (Overvliet et al., 2014) but, they regard natural fiber composites as inferior, low-quality and unattractive (Rognoli et al., 2011) and some users worry about the durability of bioplastic (Rumm, 2016). As well as conflict between the characterisation of naturalness and high quality in natural composite materials (Karana & Nijkamp, 2014).

Figure 26. Examples of material qualities included in Kingdom Vegetabile (Ayala-Garcia et al., 2017)

Material Appraisals

Users assess materials based on their intrinsic and extrinsic properties, leading to a subjective assessment of the user-product interaction, i.e. subjective feelings towards a material (Karana, 2009). For instance, the radial section of softwood evokes mellow, natural feelings and pleasant emotions (Song & Zhao, 2011). Research on material appraisal has led to the identification of seven appraisal themes as follows: (i) sensorial, (ii) technical, (iii) expressive semantic, (iv) use, (v) manufacturing, (vi) emotional and (vii) associative description (Karana, 2009). An additional appraisal theme termed systemic was proposed concerning on the lifecycle impact of materials (Bahrudin & Aurisicchio, 2018).

New research (F. Bahrudin et al., 2018) sheds light on the emotional experiences and their appraisals of sustainable materials.

Bahrudin reported that the most frequent positive emotion typology (Desmet, 2012) is gratification followed by animation and enjoyment. While negative emotion typologies are discontent, uncertainty and aversion. Mostly positive emotions were evoked with 'surprise' being the most frequent emotion. Particularly when unconventional materials were utilised. With systemic appraisals, participants appraised positively the benefits and impact of using the materials. Indicating that participants assigned value to the materials based on their understanding and knowledge of the material lifecycle derived from the material origin. This also lead to negative meanings and emotions concerned with the pragmatic utility of the materials. Typically technical appraisals were to do with flexibility and strength.

The interplay of the appraisal themes involved in the evaluation of sustainable materials indicates there may be no formula to guarantee the success. It is recommended that designing the biography of a material so that it will amplify the positive emotions to counteract the negative emotions from other appraisal themes. Alternatively, the sensorial properties of a material can also be designed to communicate the material biography, show material reliability and retain the natural look. For example, in the Wabi Sabi concept (Salvia et al., 2010), imperfection is often embraced as it communicates the narrative behind the materials.

Natural Materials

Research on ‘natural’ materials has shown that characteristics such as natural colours and patterns, that show commonalities with basic aesthetic features of nature; were described as durable or long-lasting; and had imperfect surfaces which were identified as unique or the result of traces of life (Karana, 2012).

Other material properties associations to naturalness include non-reflective, visible grains and fibres, being fairly ‘unprocessed’ or processed in such a way that the original material was still recognizable (Karana, 2012). As well as opaqueness of a material being one of the most important properties in expressing the naturalness.

Uniqueness plays an important role in the attribution of the meaning natural (Karana, 2012). Aspects that make a material unique include: Traces of life: Traces of someone’s personal life in the material (scratches, scrapes, colour change, etc.) of a product may personalize the material and increase its relevance and value to an individual. This might positively affect the formation of an emotional bond with that material and the product (Schifferstein and Zwartkruis-Pelgrim, 2008).

Relevant for bio-plastics. Randomly created surface patterns; characteristic of Imperfection, can be used as a unique property of bio-plastic materials to emphasise their naturalness. Particularly when being used as a matrix in Natural Fibre Composites (NFC’s). Surface patterns created through visible grains and fibres that are randomly distributed are directly associated to nature, where no two elements appear the same (Karana, 2012).

Below a Meaning of Materials (MoM) Model (Karana, 2009) is presented representing the dynamic action between user and a material in which the material obtains its meaning. Here it visualises data sets for the meanings natural (Karana, 2012). It presents a starting point to facilitate thinking into how to evoke the meaning natural.

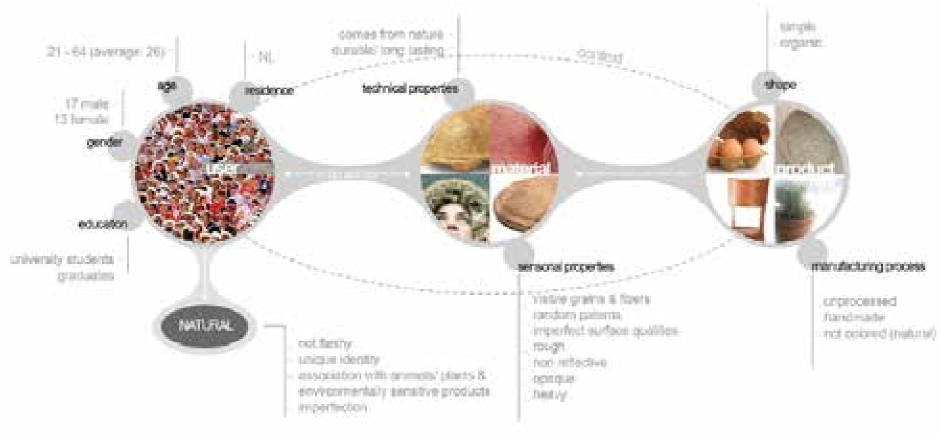


Figure 27. Visualisation of ‘natural’ data sets based on the meanings of materials model. (Karana, 2012)

Imperfection

Alongside naturalness, another aesthetic expression exists: that of imperfection. Products that fit into an imperfect aesthetic through material choices are aimed at gratifying people’s senses through unique aesthetic features and sometimes through a resemblance to material effects that occur in nature. These products are intended to generate value for people through the characteristics of graceful aging. (Elvin Karana, Owain Pedgley, Valentina Rognoli, 2015)

Traces of life that a material can carry as part of its aesthetic beauty, as they inherently valorize imperfection as a unique aesthetic feature. Giving value to the imperfect condition leads to a reconsideration of the relationship that one has with everyday objects. Imperfect aesthetic qualities of materials can be endearing and help to create an experiential bond with users (Valentina Rognoli and Elvin Karana, 2014).

The move towards imperfection is a new aesthetic that can be harnessed to elicit particular emotions (e.g., love, hate), encourage particular behaviours (e.g., to care for, to keep for longer), and impart high-level values (e.g., appreciation of the natural). A material ages with its user, matures in time, carries the traces of one’s life span, facilitates the recall of memories, and relates one to the familiar and the usual (Elvin Karana, Owain Pedgley, Valentina Rognoli, 2015).

It is proposed to use imperfection as a material aesthetic to express naturalness and to trigger unique material experiences to create richer and more enduring relationships (Rognoli & Karana, 2014). This leads to sustainable design through emotional durability (Mugge, R et al., 2008), as products can be considered unique and not readily replicable.

Figure 28. A bio-composite chair designed by Werner Aisslinger and BASF, expressing naturalness. (source: http://www.jeccomposites.com/

3.3 Love it or lose it:

Appealing patterns

It is possible to manipulate Interwoven into different pattern structures, which will be the first material property users interact with because upon first introduction to a product, our vision takes the lead (Fenko, Schifferstein & Hekkert, 2010). The visual modality dominates the experience in the beginning of the user-product relationship (Fenko, Schifferstein & Hekkert, 2010).

It is intended that the pattern on Interwoven stimulates intrigue and should also be attractive. As Hosey (2012) writes, a more attractive design discourages us from abandoning it: Long-term value is difficult without sensory pleasure, because positive associations are formed with things we consider beautiful, users are more likely to become emotionally attached keeping the object for longer, as long as they care for it. As Interwoven is a delicate material it is advantageous to design for emotional durability (Mugge, R et al., 2008) to extend the product use the material will be embodied in, as an approach for sustainable design.

Hekkert suggests that the senses experience pleasure when certain patterns are recognized, which are beneficial to our primary sense’s functioning (Hekkert, 2006). He argues that we aesthetically prefer environmental patterns, that represent *unity in variety*, as we detect order in chaos into meaningful wholes.

Using patterns from the natural world, i.e. environmental patterns utilises unity in variety that creates an imperfect look and feel. Patterns from nature combined with the naturalness of Interwoven create a novel aesthetic which adds to the already unique origin of the material. As mentioned before, imperfections that exist in the material and those that arise during its lifetime, play an important role in expressing the naturalness of a material (Rognoli & Karana, 2014). An experiential interpretation that is desired to be elicited in the material experience. Research on ‘natural’ materials (Karana, 2012) showed that characteristics such as natural colours and patterns, that show commonalities with basic aesthetic features of nature; were described as durable or long-lasting; this can be utilised for the perception of durability of Interwoven.

The novel aesthetic characterized by imperfection and the passing of time (Rognoli & Karana, 2014) of the roots journey during growth can be used to express naturalness and to trigger uniqueness in the material experience to create richer and more enduring relationships (Rognoli & Karana, 2014), leading to sustainable design.

Conclusion

Bio-composite structure is a promising method to improve the durability of Interwoven with bio-based polymers as a matrix. Long continuous fibres and good bonding from the matrix is required for adequate strength development. The use of a bioplastic should not hide the already unique imperfect aesthetic in order to express the meanings of naturalness and sustainability, characterised by the passing of time. This uniqueness of traces of life and imperfection can impart emotions, memories and build a relationship with users, leading to emotional durability and sustainable design.

> “In the end, we conserve only what we love.”
> Baba Dioum

4

Exploring Interwoven

This chapter introduces material tinkering. Understanding how to increase the strength of Interwoven to reduce uncertainty in designing with it. Further experiential and technical studies of developed samples are reviewed.

4.1 Tinkering

To tackle uncertainty in designing with a growing material, tinkering strategies are formulated before hand. This is known as a taxonomy. These strategies act as starting points for experiments and help with strategic intervention.

Taxonomy

As described in the Material Driven Design (MDD) method (Karana, 2015), tinkering with the material is used as the first step of understanding a certain material. It aims to get insights on what the material affords, its technical properties, as well as how it can be shaped and what the material affords. It acts as initial assumptions to guide the experiments.

The tinkering phase determines what variables can be altered to effect specific properties. For example, varying the amount of seeds used can determine the density of the material. However, this can also influence the texture that can be achieved. Therefore a change in one variable can influence other properties.

Tinkering with Interwoven is suggested in four directions; *(1) material ingredients (2) growing conditions (3) material structure (4) material processing.* The taxonomy illustrated below summarizes what specific variables can be altered to change material properties. The following pages document the insights gained from the tinkering process.

Figure 29 . Image of variation of different tinkering exploration with Interwoven

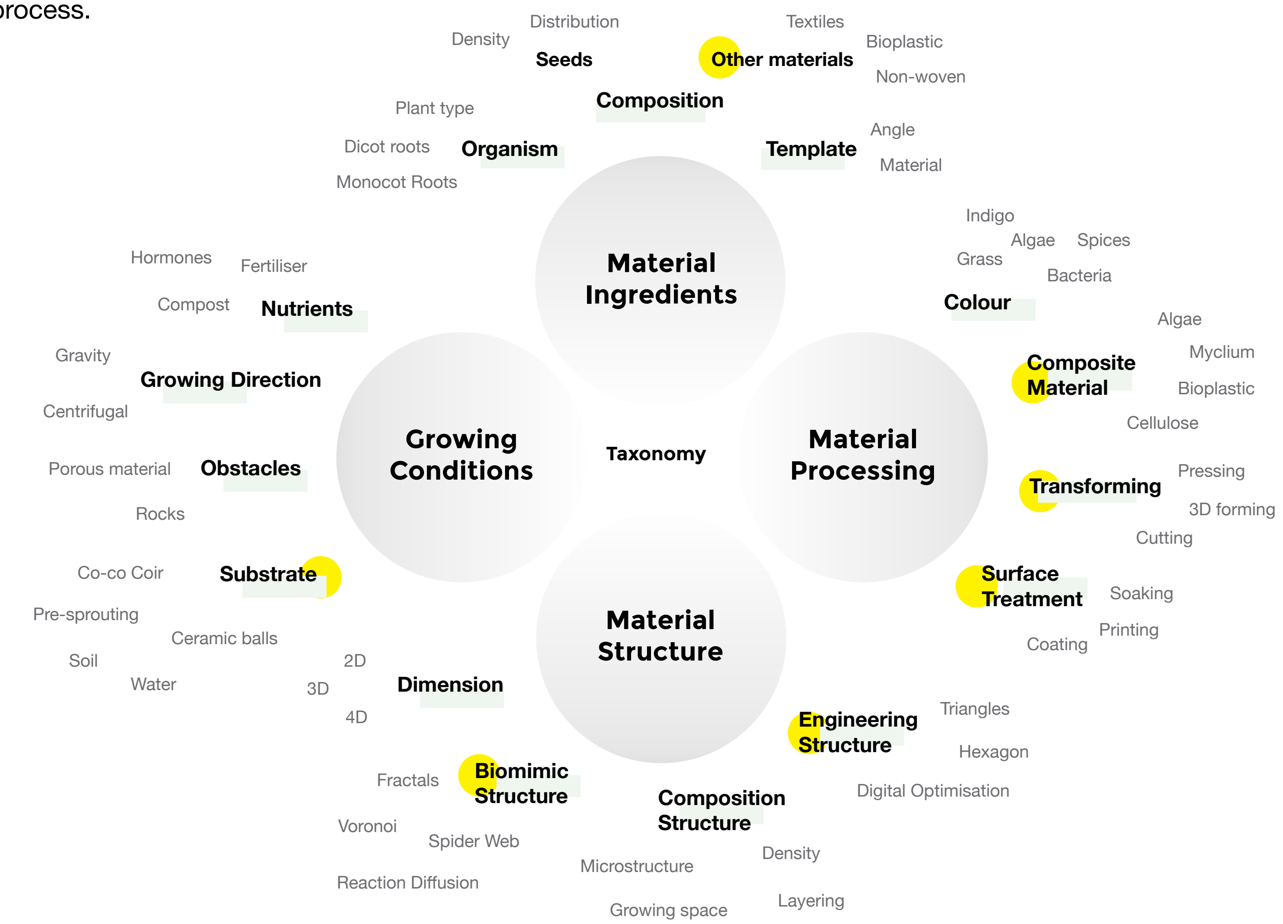


Figure 30 . Taxonomy for tinkering directions. Yellow indicates areas where tinkering was explored.

4.2 Growing Conditions

Substrates

The oat roots behave differently in different growing substrates. Soil, agar, co-co coir, water and bioplastic were tested as substrate for growing conditions.

Insights

Soil Depth: When growing in soil the roots performed the best in regards to being compact and tightly weaved together. With less than 5 cm of soil the oat leaves would struggle and the roots would be small and frail. This could be due to less soil for anchoring the roots.

Tasty agar: The roots grew very quickly when agar was added to water and used as a substrate. The roots seemed to suck up the water and leave the agar behind. This created a natural composite as the agar encased the roots and made them hard. A unique feature of this is that when added to water the roots would become soft again and easily pliable.

Co-co coir fibre: Is a fine powder and is easy to recycle for another batch of growing. However the root quality was less than with soil.

Water and ceramic balls: Both allowed the roots to grow quickly with a high density of roots, but the roots were left stringy and less compact together making a weak structure.

Oxygen starvation: When the roots become starved of oxygen they change colour and become darker brown.

Figure 31. Examples of different substrates used

4.3 Material Ingredients + Structure

Structures
The roots show affordance potential to be manipulated into different pattern structures in the growing process.

Insights
Organic and structured patterns can be utilised for aesthetic expression, texture and symbolic meaning. Linear patterns are better connectivity.

Roots create different effects when subject to different mould shapes. The roots fill linear channels, binding together to create a pattern. When subject to holes they swirl downwards and create a woolly-like effect.

Mould depth effects the root structure. Deeper moulds will provide a thicker sample but with less interconnectedness between the pattern. Whereas shallow mould allow for connection of roots between the patterns.

Ingredients
The roots will grow through other materials. A textile and non-woven jute matt were used to experiment.

Insights
Roots act like stitching. The roots were able to effectively grow through two textiles binding them together with an organic pattern structure. Similarly the roots grew through a non-woven matt into a geometric structure.

Other substrates can be added to create a composite. For example agar can be added to a non-woven to act as a substrate. The roots will grow through the non-woven and the agar leaves the sample rigid and stiff.


Textile with organic pattern


Pattern structure


Change in thickness


Woolly-like effect


Non-woven, geometric pattern

Figure 32 . Examples of different structures available

4.4 Experiential Analysis

To understand the difference of experience between geometric and organic patterns an experiential characterisation study was conducted.

Introduction
The material experience on all levels is investigated of two different samples. One sample having a geometric pattern, grown through a non-woven jute matt. The other being an organic pattern, grown through a textile.

Aim: *Uncover interrelationships between the experiential levels. Identify which pattern structures are associated with a particular meaning, which should be kept or modified.*

The test set up, method and analysis is kept the same.

Participants
Age 22 - 27
Six participants from the Industrial Design faculty of Delft University of Technology participated. Each a design masters student. None were familiar with the material.

Belgium, Dutch, German, Italian
n=6

Results
The analysis of the data is qualitative, due to the limited number of participants. The following pages show the main takeaways, which are then discussed. To uncover individual appraisals, the seven themes of Karana (2009) were used to categorise, with the addition of a systemic theme introduced by Bahrudin. F, 2018.

In this section only the performative and sensorial levels are discussed because they are the most relevant to perceptions of durability and delicateness. To view the full discussion see appendix B.

The organic pattern is represented as **T1** and the geometric pattern is represented as **T2.**

Samples

T1 T2

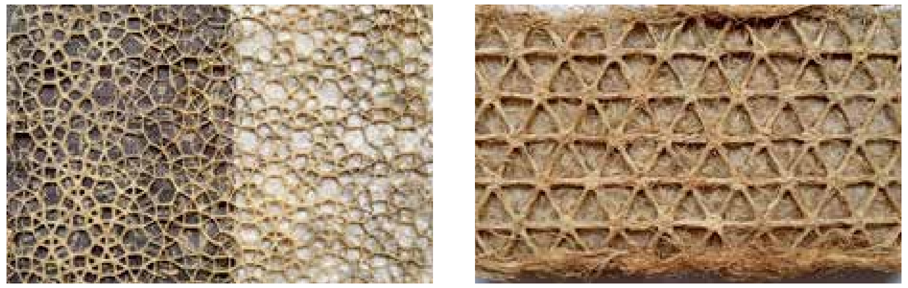


Figure 33 . Images of material samples analysed for experiential study

Main Takeaways

Most relevant to project

Sensorial

1. **Regular durability**
Individual strands of fibre are considered weak but the regularity of a pattern elicited the perception of durability.

2. **Stimulate exploration**
Participants rubbed to explore and to understand the changes in the depth of texture.

Performative

3. **Delicate behaviour**
The roots architecture look delicate and evoke careful interactions and behaviour.

Affective

4. **Respect to nature**
The origin of the material plays a strong role in positive emotional appraisals and associations of connection to nature.

Interpretive

5. **Hopeful future**
Root architecture evokes natural interpretations and associations of living in harmony with nature in the future.

6. **Imperfection is naturally cosy**
Imperfect aesthetic in the material, through rough tactility, natural colour, and imperfections evokes natural and cosy interpretations.

7. **Unique Origin**
The life cycle of the material is positively appraised as sustainable when considered from a systemic perspective. I.e. cleans CO_2 and is a renewable resource.

(1) Performative

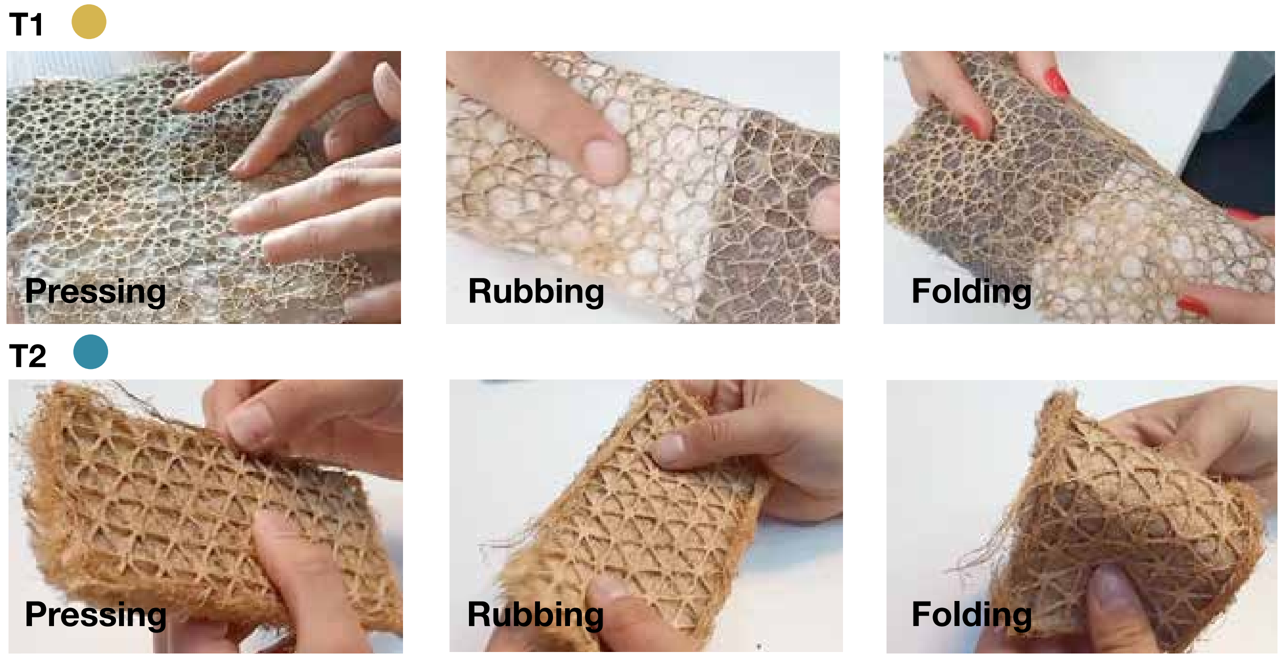


Figure 35. Images of interactions with samples

Pressing n= 6/6 - Sensory exploration
Rubbing n= 5/6 - Affective response
Folding n= 4/6 - Technical exploration

Performative Level

The most common interactions are pressing (5), rubbing (3) and folding (4). **The quality of pressing was done delicately at first to explore the sensory stimulation of the raised roots and feel through rubbing the tactile roughness of the roots in contrast to its lower material. As understanding of the materials grew participants began to use them with more confidence by bending or folding to test its practical boundaries, although this was also done with carefulness.**

Discussion
The pressing was initiated with the sensorial visual contrast between the roots and textile or the visible depth between the roots and the underlying material because participants were trying to understand the difference between the top and bottom materials. Bending and folding were technical explorations to test the materials practical performance.

The non-woven material was considered more durable because the pattern is a constant tessellation of triangles, a strong structure from engineering, as well as being thicker than the other textile sample.

Sensorial Level

The material is considered to be mostly **soft, rough, matte, not reflective, warm, not elastic, opaque, ductile, strong but also weak, light, fibrous, regular.**

Discussion
Both materials were considered soft, because of the ability to be compressed slightly. This is more apparent in the non-woven material. The rough tactile qualities were stimulating for participants to rub and to explore. It was considered a nice contrast to have two qualities that you wouldn't expect together, such as rough and soft or similarly, a regular geometric pattern that feels soft.

Discrepancies in strong and weak are to do with the visual strength of the patterns, the regular organic pattern of the roots on the textile was considered to add strength. This is the same with the regular triangle pattern of the non-woven because collectively together they are perceived as stronger but as individual strand, the participants knew that the origin of the material was considered weak.

(2) Sensorial

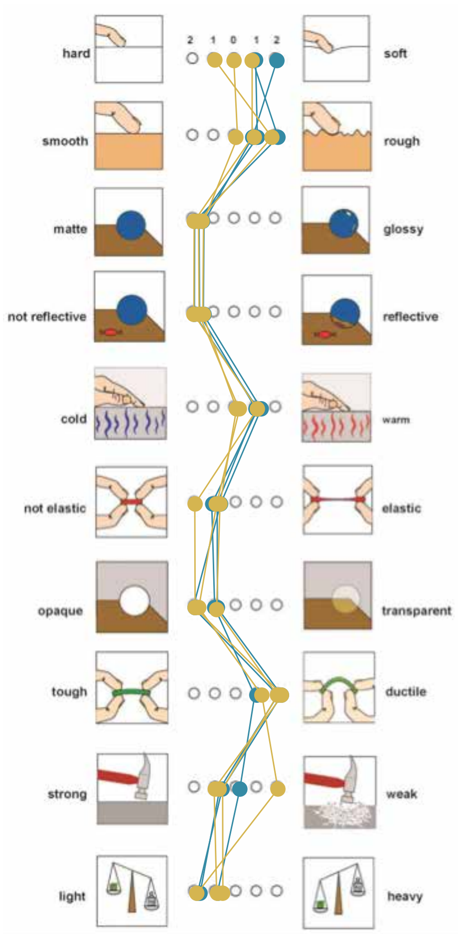


Figure 36. Sensorial scale results

4.5 Material Processing

Transforming

The roots show the potential to transform the form of Interwoven with the addition of bioplastics and secondary processes.

Insights
With the addition of alginate bioplastic onto a single layer of Interwoven, the bio-composite can be 3D formed with cold pressing techniques.

Additionally the alginate and pectin samples can be folded and pleated into different forms. Pectin particularly can be creased and return to its former position.

Heat pressing techniques can be applied to create rigid and stiff areas..

Heat pressing in certain areas can create soft hinges between the stiff and rigid areas.

Heat pressing makes the samples smell like caramel.

Cold forming alginate sample

Pleating alginate sample

Heat pressing with PLA bioplastic

Surface Treatment

The roots can be treated with different surface coatings. The different surface coatings tried are: *beeswax, carnauba wax, latex, shellac, pine rosin, and ghee.* As well as combinations of these.

Insights
Surface coating do not improve the strength but change the tactile properties of the roots.

Beeswax, carnauba wax and latex are water resistant. Although the latex leaves the sample sticky to touch.

Beeswax changes the colour of the roots to be more golden.

Pine rosin and shellac become rigid and shack under small forces.

Surface coating the fibres, effectively removes the roots hairs, which creates holes in the samples.

Beeswax coating

Carnauba wax

Latex

Shellac

Figure 37. Examples of different processing results

4.6 Bioplastics

The use of bioplastics as a matrix to create a bio-composite is one method to increase strength. A recent visit to the Waar Society in Amsterdam with Diana Scherer allowed for some recipes to be discovered. The following is an over view of some of the recipes used for making bioplastics.

Figure 38 . Initial samples of alginate bioplastic made at Waar Society

Equipment
Cooking pot, spoon, electric scale, electric burner and measuring beaker.

Process
1. Heat water.
2. Add biomass to the pot and stir to break up the particles.
3. Add glycerol and mix.
4. Simmer until viscose.
5. Remove from heat and allow to cool slightly.
6. Layer the bioplastic with a brush.
7. Use baking paper to press the bioplastic and material together.
8. Let dry for 12 hours

Gelatine
Glycerol 7.2g
Water 60ml
Gelatine 12g

Agar
Glycerol 5.4g
Water 40ml
Agar Agar 1.6g

The same quantities were used to make pectin bioplastic.

Corn Starch
Glycerol 10g
Water 80ml
C starch 1.6g
Vinegar 15ml

Alginate
Glycerol 5.4g
Water 150ml
Alginate 12g
Calcium chloride 48g
Water 200ml

Please note: The process for alginate is different to the others. Glycerol, water and alginate can be blended until viscose without heat. The calcium chloride and water are mixed separately. The material sample is sprayed with the calcium solution. The bioplastic must be poured and smoothed over the surface (like screen printing). Then spray the calcium solution to finish.

Pectin Alginate Gelatine Agar Corn

Figure 39. Bioplastic samples

Bio-composite
The roots show the potential to be process with bioplastics to make bio-composites.

Insights
Bioplastics can be applied with a brush, while still retaining the visual aesthetic of the root architecture.

More glycerol can be added to make the bioplastic more flexible. Too much and it doesn't set.

Pectin and gelatine shrink the least and so do not effect the roots overall form. Whereas agar shrinks a lot and disrupts the form.

Corn cured quickly and quick action is required. It was the most difficult to apply to Interwoven's delicate roots.

Pectin remains cool to the touch and changes the colour of the roots slightly.

Colour of the bioplastic can be changed depending on the length of time the solution is left cooking.

Alginate requires that the process is done on both sides to encase the roots. Alternatively it can be used as a surface coating on one side.

Major advantage of alginate is it is water proof and will only dissolve in the presence of baking soda solution.

Alginate can be applied to single layers of Interwoven. The final effect is a paper-like quality that is shiny but textured.

Colour dyes can be added to alginate bioplastic solution to create different colours.

Two or three layers of random homogeneous Interwoven can be added with pectin, gelatine and alginate bioplastic. By pressing the layers together.

Bioplastic matrix protects the roots and maintains their position.

Corn Starch surface

Alginate surface

Pectin surface

Alginate with green dye

Gelatine surface

Agar surface

Alginate on pattern surface

Figure 40. Examples if bio-composites

4.7 Technical properties

The strength and structure are most relevant technical aspects of this investigation. Therefore, a tensile test and microscopic examination have been conducted.

Method

The test takes reference of Standard ASTM D5034- 09 (Standard Test Method for Breaking Strength and Elongation of Textile Fabrics). However, due to the fragility of Interwoven, the test method is adjusted to suit the available materials. The dimension of test specimen is adjusted to 20mm wide by 100mm long. The elongation rate is set at 2mm/min to ensure slow change in load. The failure criteria is 12mm of standard travel constant for all samples. The test provides a basic idea of the load bearing ability the current material. Therefore the differences from the standard is accepted.

Samples

Four groups of materials are chosen for the test: Two layers of Interwoven are combined with alginate, pectin and gelatine of random homogeneous order. Plus one more of a voronoi pattern with alginate. Each group has 3 samples, cut in strips. Admittedly, the 3 samples of the same group are not identical, because of the randomness of the roots autonomy during growth. Prior to testing, the samples were accurately measured (weight, length, width and thickness (0.4 - 1mm)) to ensure a proper comparison.

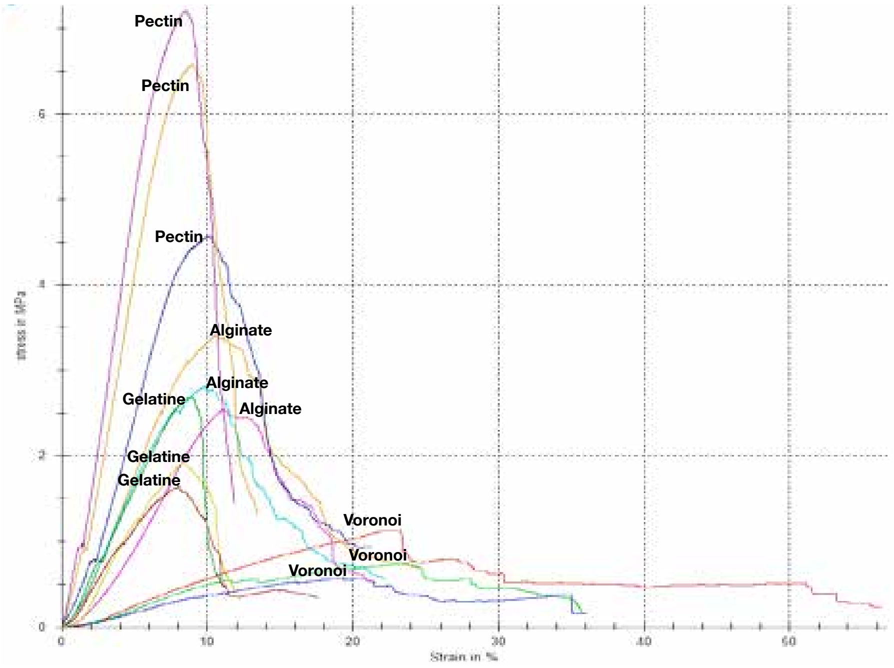


Figure 41 . Stress Strain Graph of Results

Results

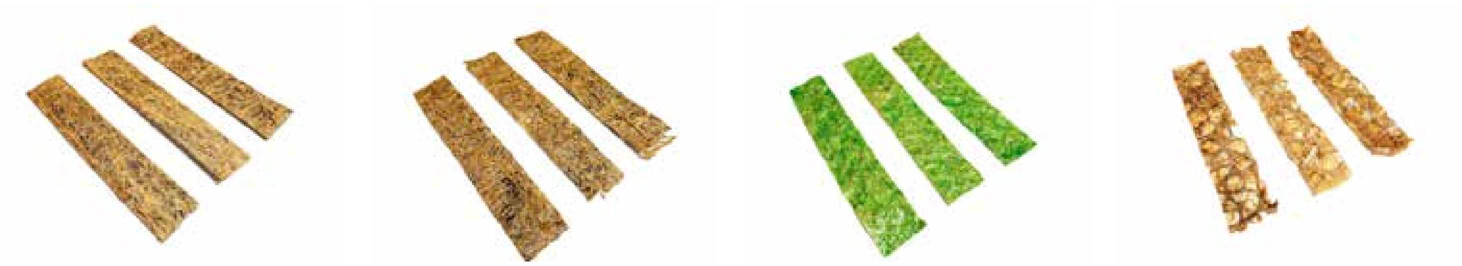
The units are in megapascals (MPa) for a comparison of internal pressure, defined as one newton per square metre.

The tested specimens show varied tensile strength (figure). The test results show that the average tensile strength of pectin is around 7.2MPa. For alginate it is around 3.45MPa. For gelatine it is around 2.5MPa and for alginate voronoi it is around 1.2MPa. Alginate voronoi will not be included in the discussion.

Discussions

The properties of a composite are determined by the properties of the fibres. We saw in an earlier test that the fibres are weak (3.2MPa) in comparison to cotton. Here the strength has been increased. Even if by a marginal amount, this is because the fibres are still inherently weak. Each sample had a random homogeneous orientation (apart from one) of fibres and so it was expected that they would perform well, especially when combined in two layers. However the strength depends on the density of the samples and the bonding of the bioplastics. The matrix acts to distribute the load, reinforce the fibres and provide structural stability. Therefore the mechanical properties are likely to vary depending on the proportion of fibres and matrix, as well as the orientation of the fibres themselves.

Pectin performed the best, this can be due to good bonding and distribution of the matrix, creating greater stability of the root fibres. Alginate is a surface treatment and so the bonding can be similar to a sandwich, allowing the fibres to slip within the bioplastic.



Pectin samples | Gelatine samples | Alginate samples | Alginate samples

Random homogeneous | Voronoi pattern

Figure 42 . Samples before testing

Microscopic View

The samples have been taken under a microscope (4.5x) to investigate its micro-structure. The following images of the samples show the before and after the tensile tests.

Currently, the pectin sample did not tear but the fibres slipped and splintered similar to wood. Suggesting good cohesion with the root fibres and distribution of load. The alginate sample indicates that the roots failed before the bioplastic, suggesting the bioplastic bonded with the surface only. Gelatine has a clear tear with a relatively straight edge to it, implying that the bioplastic made the roots more brittle. The chemical reason for this is unknown, but explains the low tensile strength.

Takeaways

Of the three different random homogeneous bioplastic samples, pectin exhibited the greatest resistance to force.

The microscopic exam shows pectin has a good ability to bond with the roots. The splintering effect suggests its able to distribute the load, reinforce the fibres and provide structural stability. Greater than the other bioplastics tested.

The fragility is still a constraint, and so adding additional layers of interwoven fibres with a mixture of fibre orientation and pectin bioplastic should increase the strength further. Providing the pectin matrix surrounds the layers evenly.

Adding more glycerol to the pectin bioplastic can increase the flexibility.

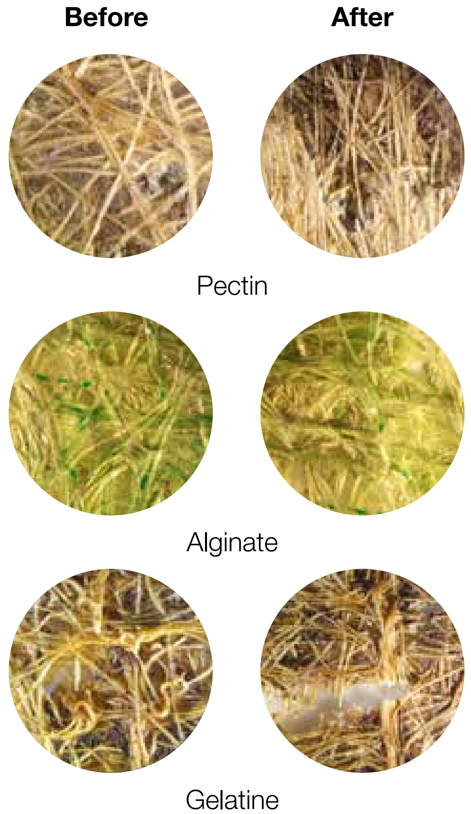


Figure 43 . Samples under a microscope (4.5x)

4.8 Experiential Analysis

To understand the difference of experience between the bioplastics experiential characterisation study was conducted.

Introduction

The material experience on all levels is investigated four samples. Pectin, alginate, agar and gelatine.

Aim: *Uncover interrelationships between the experiential levels. Identify which meanings, emotions or sensory qualities should be kept or modified.*

The test set up, method and analysis is kept the same.

Participants

Age 23 - 31
Background: Design masters students from Industrial Design and Engineering at TU Delft. Indian, Dutch, Mexican, Italian, USA n=12

Results

The analysis of the data is qualitative, due to the limited number of participants. The following pages show the results, and the main takeaways. To see the full discussion see appendix B. To uncover individual appraisals, the seven themes of Karana (2009) were used to categorise, with the addition of a systemic theme introduced by Bahrudin. F, 2018.

Samples

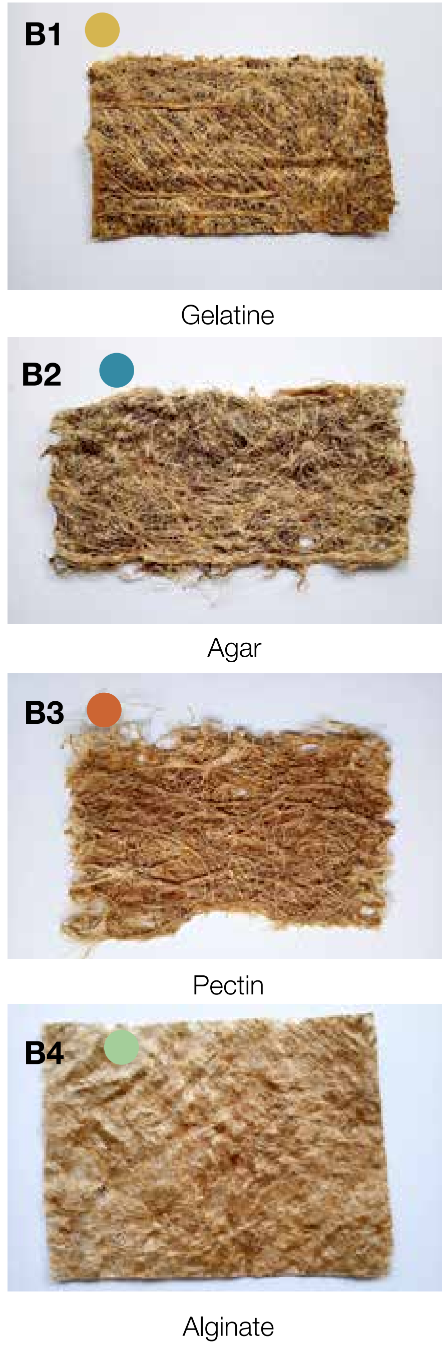
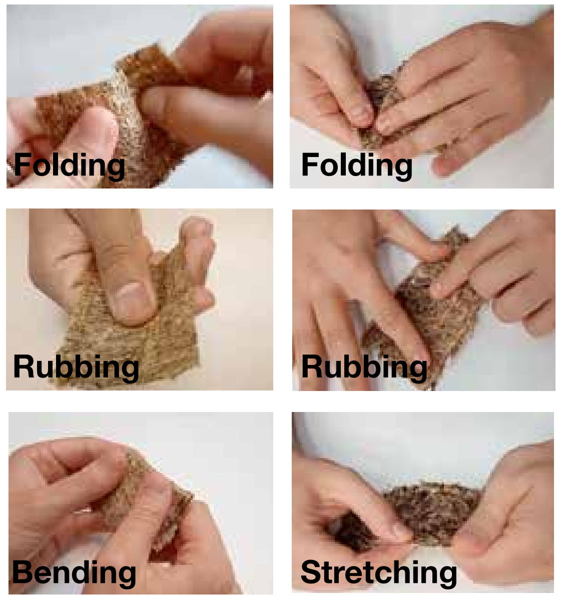


Figure 44. Examples of bio-composite samples to be tested for experiential characterisation.

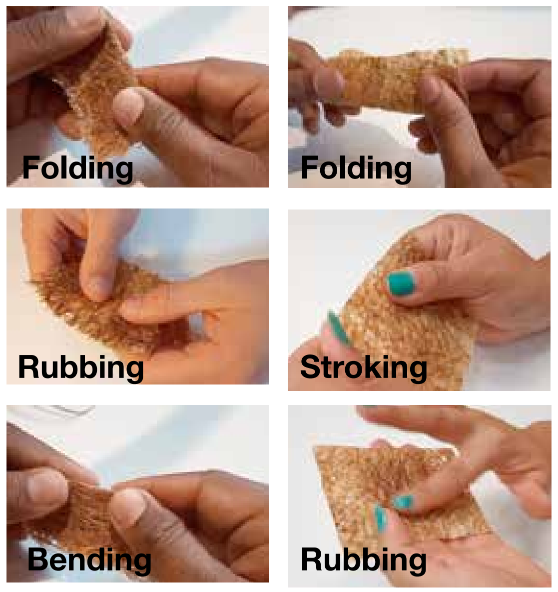
Bioplastic Results

(1) Performative

B1 B2

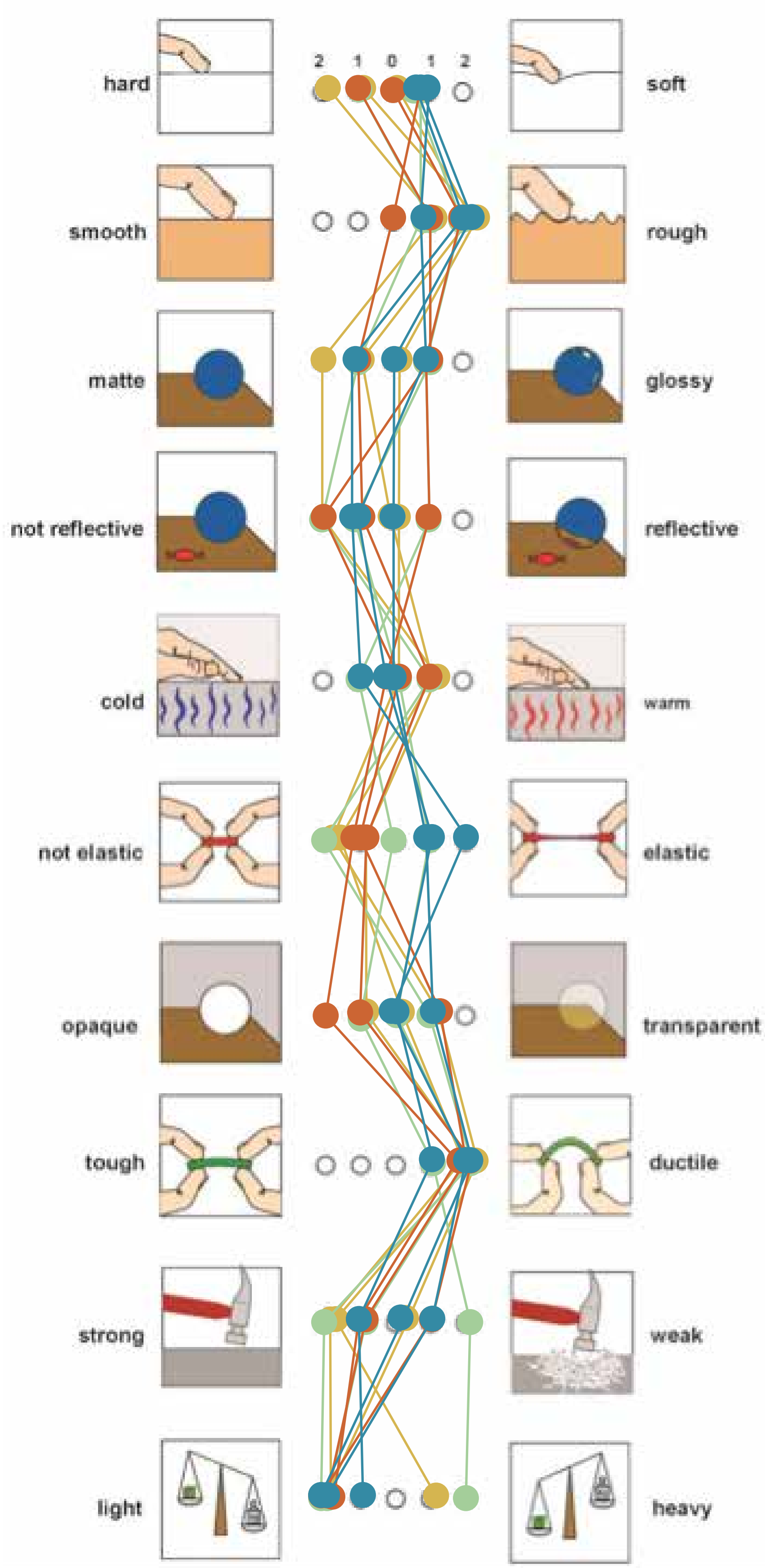


B3 B4

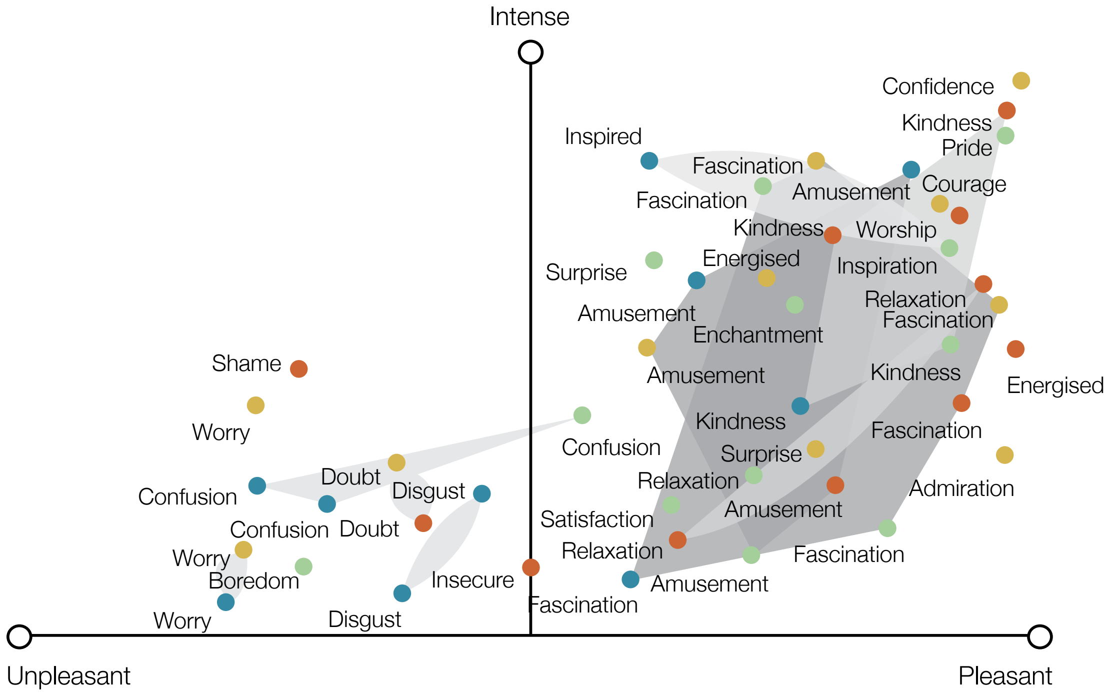


Rubbing n= 11/12 - Sensory exploration
Folding n= 8/12 - Affective response
Bending n= 10/12 - Technical exploration

(2) Sensorial



(3) Affective



(4) Interpretive

Natural n=8/12

Handcraft n=8/12

Nostalgic n=5/12

Delicate n=4/12

Durable n=3/12

Strange n=3/12

Other meanings: Elegant, aloof, sober, calm, frivolous n=1/12

Associations

Durable materials & products

"Like a tent material"
"Plastic like"
"Compact composite"
"Similar to a canopy"
"I see it as part of a backpack"
"Like a leather replacement"
"Bag or chefs apron"
"Car seat cover"
" Watch band"
"Reminds me of the underside of a shoe"

Nostalgia

"Reminds me of my childhood"
"Reminds me of a temple in India"
"Reminds me of Indian jute bag"
"Like a jute fabric bag"
"Reminds me of a cottage by the sea"

Connection

"Something chaotic, reinforces natural causality"
"Like chaos"
"Could be a yoga matt"
"When nature takes over"

Natural products & materials

"Like a carpet beater"
"Like broom made of coconut tree spine"
"Could be a wall feature for a natural look"
"Reminds me of cardboard or cork"
"Like burnt skin"
"Like paper"

Main Takeaways

Takeaways of particular interest are underlined in red. This indicates an insight into the perception of delicate or durable qualities to be kept or modified in the development of Interwoven.

Sensorial

1. Rough and Durable
The natural colour, visual roughness and flexible properties were associated to durable materials.

2. Synthetic Strength
Glossy surface quality is perceived as stronger but with unnatural or synthetic associations.

Performative

3. Customised by nature
Root architecture is untameable and unique for each piece, being super customised by nature.

4. More you look, more you see
The irregular, heterogeneous fibrousness are imperfect qualities that encourage exploration.

5. Delicate Rubbing
Rubbing performed with delicate interest to explore the roots.

6. Organised strength
Perception of strength known to be in direction of fibres by participants previous knowledge of composites.

7. Sensorial biography
Roots represent symbolic connection to nature and elicit deeper personal reflection to relationship with nature.

8. Natural interpretations
Imperfect qualities with rough and textured tactility is considered natural.

Interpretive

9. Perceived delicateness
Heterogeneous root composition with semi-transparency provokes delicate interpretations.

10. Trustworthy layers
Greater homogeneousness of irregular fibres, with visible layers was perceived as durable and more trustworthy.

11. Afraid it will break
Knowing origin of the material creates uncertainty in technical performance and doubt in its long term use.

12. Unfamiliar fascination
Signs of bioplastic matrix with imperfect root architecture is novel aesthetic and sparks interest in how it is made.

Affective

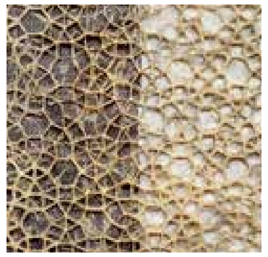
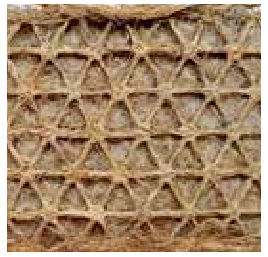
13. Spark amusement
Contradicting material qualities such as looking rough and textured but feeling smooth sparks amusement.

14. Repeat satisfaction
Alginate and pectin bioplastic don't crease, which elicits more confidence and positive emotional appraisals.

15. Humble Pride
Humility is experienced towards the material and pride reflecting personal values towards environmental concerns.

The following page will provide an overview of the experiential findings from all the characterisation studies.

4.9 Experiential Summary

			Performative	Sensorial	Affective	Interpretive	Association	Final Reflection
Interwoven 1.			Pressing, **rubbing**, pulling, caressing, **folding**, lifting, looking through, **bending**, smelling, stroking and squeezing.	Soft, rough, matte, not reflective, warm, not elastic,opaque but transparent, ductile, mostly weak but slightly strong, light, fibrous and irregular.	Respect, kindness, worship, surprise, fascination, satisfaction, shame and worry.	**Natural, nostalgic, handcraft**, sober, delicate and feminine.	Mother Nature, burlap sack, lamp shade, close to God, close to Earth, monk material, Arabic mosque.	Heterogeneous and irregular root architecture is most pleasant. Most unique is the origin of the material and that it can be manipulated into any pattern. Most disturbing is the soil and residue.
Pectin 2.			Pressing, **rubbing**, compressing, **folding**, fiddling, **bending**, lifting, holding, smelling, rolling.	Soft and hand, rough, a little glossy, not very reflective, warm and cold, not elastic, opaque but a little transparent, ductile, weak, light, irregular, fibrous.	**Kindness, relaxation**, energised, amusement, fascination, worship, shame, doubt, insecure.	**Natural, nostalgic, handcaft**, ordinary, delicate, cosy, calm, frivolous, futuristic.	Underside of shoe, burnt skin, suit, yoga matt, temple in India, jute bag, natural causality.	
Alginate 3.			**Rubbing**, stroking, compressing,fiddling, **folding**, **bending**, tearing, rolling, smelling, crumpling, holding.	Soft, rough, glossy,not reflective, cold and warm, semi-elastic, opaque but a little transparent, ductile, strong, light, irregular, fibrous.	**Fascination,** enchantment, inspiration, relaxation, satisfying, kindness, amusement, surprise, pride, boredom, confusion.	Elegant, **nostalgic**, **delicate,** aloof, **natural**, durable, strange, handcraft, sober.	Like paper, tent material, plastic-like, like chaos, wall feature, cottage by the sea, blanket, cardboard, cork, compact composite.	Natural look and feel through natural colour, randomness of fibres and roughness, invited toughing. **Sensorial Originality** of material considered most unique with visible root architecture, and customisation by nature making it novel. Most disturbing is the insecurity with its technical ability.
Agar 4.			Pressing, **rubbing**, **stretching**, fiddling, **folding**, bending, flexing, lifting, smelling, grabbing.	Soft, rough, matte, not reflective, cool, elastic, sort of transparent, ductile, strong, light, irregular, fibrous.	Kindness, **amusement,** inspired, fascination, confusion, disgust, worry.	**Natural, nostalgic, handcraft**, strange, delicate.	When nature takes over, bracelet.	
Gelatine 5.			Pressing, **rubbing**, compressing, fiddling, **folding**, **bending**, smelling, holding	Hard, rough, matte, a bit reflective, warmer, not elastic, a bit transparent, ductile, strong, light, irregular, fibrous.	**Fascination,** amusement, surprise, energised, courage, confidence, admiration, worry, doubt.	**Natural, durable, handcraft,** nostalgic, strange, delicate.	Canopy, bottom of backpack, leather replacement, jute bag, watch band, seat cover, chefs apron.	For this project it is seen that experience is the main material potential. In appendix B you will find an explanation of the potentials across the material experience levels.
Organic pattern 6.			**Pressing**, **rubbing**, compressing, **folding**, poking, smelling, holding.	Soft and hard, rough, matte, not reflective, warm, not elastic, opaque, ductile, strong, light, regular, kinda fibrous	**Respect, energised**, relaxation, dreaminess, joy, fascination, enchantment, reluctance.	**Natural, cosy**, nostalgic, handcaft, futuristic	Tribe like, trolls, hobbits and stuff, bathroom floor, fuzzy beard, walking in nature, roots take me to a world i never lived in, good at pretending to be something its not.	Expressive semantics such as warm and Earthy feel, created through natural colour, rough tactility and imperfect qualities were considered most pleasant. Most unique is to do with origin in regards to life cycle of the material, and that it removes CO2 out of the air in production.
Structured pattern 7.			**Pressing**, pushing, **compressing**, **folding**, picking, squeezing, smelling, holding.	Soft, rough, matte, not reflective, warm, not elastic, opaque, ductile, medium strength, light.	**Kindness**, fascination, inspiration, dreaminess, joy, relaxation, insecurity, confusion.	**Natural, futuristic cosy,** handcraft, sober.	Packaging, hemp fibres, pillow, bottom of shoe, relaxing matt, sitting by fire place, terraced farming, cloud.	

4.10 **Experiential** Insights

By capturing the users perceptions with the material experience model, it is clear that the four levels of experience are all closely interrelated in a multidimensional way. Looking at the main takeaways, there are recurring material qualities that can be clustered and summarised to support the development Interwoven towards creating meaningful relationships. This is important because products that give meaning to users will likely be positively regarded and potentially shorten the gestation period of this emerging material.

1.

Sensorial Originality

The sensory properties of the material can be used to communicate the materials origin (Bahrudin, et al., 2018). In order to amplify the positive reactions elicited in the materials experience, because it was recognised that the materials were appraised positively when assessed to systemic themes; as *users preconceptions and world views set the kind of sustainable issues prioritised* (Wilkes, 2014). Particularly now-a-days as people are very aware of the ecological impact of materials and the need to shift towards environmentally benign materials. The essence of the sensorial quality that should be kept and emphasized is the roots architecture and visible behaviour of the roots, as this has interpretations of being natural and expresses traces of its growth, carrying the biography of the roots journey into the material. The heterogeneous irregularity and *"untamed"* fibrousness, which has a rough looking texture creates an imperfect quality that is aesthetically pleasing. These sensorial qualities valorise imperfection (Rognoli et al., 2015), and become active stimuli for users cognitive and affective responses. Additionally the roots behaviour is uncertain and so its adds value to each material piece being unique and one of a kind, customised by nature.

2.

Symbolic Connection

The material has the potential to establish emotional and meaningful attachment because of its strong symbolic meaning. The imperfect quality invites touching, and creates a tactile connection to nature. When considering its origin and delicate root architecture, reflective emotions of humility and kindness are elicited, in association to interpretations of natural, handcraft and nostalgic. These interpretations are to do with memories of the personal past, and our collective existential past with nature, as the roots reminded people of their *"symbiotic relationship with nature" with reference to "returning to something that was you all along".* Additionally the heterogeneousness of the imperfect aesthetic contained within a single form, coming together as one is symbolic of humanities group affiliation and our connectedness to the natural world. This meaning of connection could create longer lasting product attachment, stimulating *emotional durability* (Mugge, R et al., 2008). As each piece is unique, its special meaning can not be readily replaced and could therefore be considered irreplaceable. The key component of emotional durability. Furthermore, people experienced *ideological pleasure* (Jordan, P.W, 200) as it elicited positive emotions of self expression representing ones values and outward self perceptions. Symbolising one's beliefs of sustainability. The pattern structure should be manipulated to represent the connection to nature by using patterns from nature while keeps the imperfect qualities, that evoke the interpretations of natural, nostalgic and handcraft.

3.

Delicate Durability

The imperfect quality due to the materials origin evoked delicate interpretations and careful interactions, particularly the heterogeneous root architecture. This created value towards the materials based on the known origin and life cycle, as it was identified as bio-based and biodegradable. However the knowledge of its origin also raised concerns on the potential use and technical performance of the materials as participants explored its strength during interactions. This can be *attributed to unfamiliarity with the material and expectations in comparison to others* (Bahrudin et al., 2018), as people try to perceptually categorise the material. In order to mitigate uncertainty and doubt of technical appraisals, *tactile and visual ques of the materials aesthetics can be used to show the materials reliability while retaining the natural look and feel* (Bahrudin et al., 2018). This can be achieved through the natural colour, tactile roughness and the flexibility of the material as these qualities were associated to durable materials. Additionally visible layering of the heterogeneous material structure can create more homogeneousness to elicit the perception of durability. The patterns used should also contain regularity, and order as this elicited durable perceptions. The advantage of layering the pattern structures is that regular and ordered patterns can be used with less ordered and random patterns on the top layers to retain the imperfect sensorial quality, evoking delicate interactions, while retaining perceptions of durability.

4.

Affective Stimulation

Emotional experiences are elicited by objective and subjective experiences from the materials. The experience of meaning, evoked through cognitive processes like interpretation gave rise to reflective emotions such as kindness, pride, respect, humility and shame, but ultimately the interpretations were elicited by the sensorial or aesthetic aspects of the imperfect quality of the materials root architecture. The unfamiliarity with the aesthetic evoked sensorial pleasure, with emotions like fascination and surprise. Additionally, some participants were surprised by the how some of the materials feel because of a perceived expectation being different to their perceptions, for example, alginate bioplastic looks organic but felt paper like or similarly the pectin bioplastic looks rough but feels smoother. This incongruity of the visual and the tactile sensorial qualities with its unfamiliarity led to longer satisfaction. Further amusement was stimulated because of the flexibility and technical ability to crease and return to its former. These qualities expressed through the different bioplastics could be used together. The pectin bioplastic as a binder for its strength, as this was found to have the highest tensile strength from the technical characterisation, combined with alginate as a surface coating process. It is also found that alginate is water resistant, which has utility advantages as a bio-composite.

4.11 Conclusion

Taking the biology of the roots, all the technical characterisations, tinkering and the experiential characterisations into consideration, the following is a summary of the main findings.

Durability

Technical Durability
The strength can be increase as a bio-composite structure with pectin as a bioplastic matrix. Pectin bonds well with the roots, providing structural stability. Greater homogeneousness and density through a cross-sectional area increases the amount of root hairs and internal connectivity, contributing to the strength. Cultivation interventions can be used such as adding more seeds, plant vitamins, drought and greater soil depth to increase root anchoring, speed of growth and strength. Additionally, surface treatments can be used, such as beeswax to create resistance to water.

Layering Interwoven, fibre orientation and percentage of bioplastic to fibres will also have an effect on the strength.

Perceptual Durability
The imperfect aesthetic qualities of a natural look and feel are perceived as durable. These sensorial qualities are created through the root architecture. They include the rough tactility, looking rough, random, irregularity of the fibres and natural colour. These visual and tactile ques can be used to show reliability to reduce technical uncertainty. Additionally, fibre direction, visible layering and using patterns that contain regularity elicit durable perceptions.

Emotional Durability
Users perceive the materials as unique because of the origin of the material. Expressing the sensorial biography of the root architecture results in an imperfect aesthetic that shows traces of its growing behaviour, which carries the biography of the roots journey into the material. This creates an evocative connection to the material, which is significant for building a lasting relationship that can lead to emotional durability.

Connection to Nature

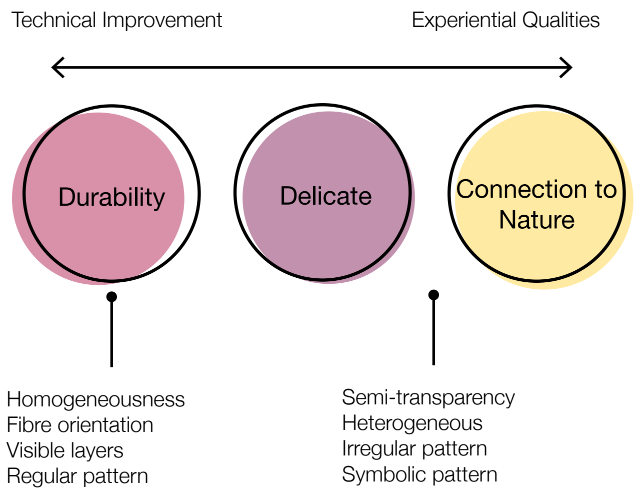
Symbolic Pattern
The imperfect quality invites touching, and creates a tactile connection to nature. The root structure can be manipulated to patterns from nature, to symbolically represent connection. Systemic reasoning of sustainability creates ideological pleasure, representing personal values.

Delicateness

Technical Delicateness
The roots are inherently weak, requiring little force to break them. A heterogeneous roots system would be less strong than a homogeneous roots system due to less root hair connectivity. Patterns with larger holes do not perform well under force.

Perceptual Delicateness
Aspects of the imperfect aesthetic are considered delicate. These qualities are; semi-transparency, some holes or rather a heterogeneous root system with organic irregularity in the root pattern structure. Additionally the fine root architecture is interpreted as delicate.

What a dilemma



A design dilemma is presented. There needs to be homogeneous connectivity, visible layering and specific fibre orientation for technical improvement. However, delicate interpretations and actions are evoked through the heterogeneous and semi-transparent qualities. A balance needs to be found.

One method is to layer the pattern structures. Linear fibre orientation and regular, ordered patterns can be layered with less ordered and random patterns to create a homogeneous effect while still retaining semi-transparent heterogeneous qualities.

The next page presents an illustration of the main findings, represented on the levels of materials experience.

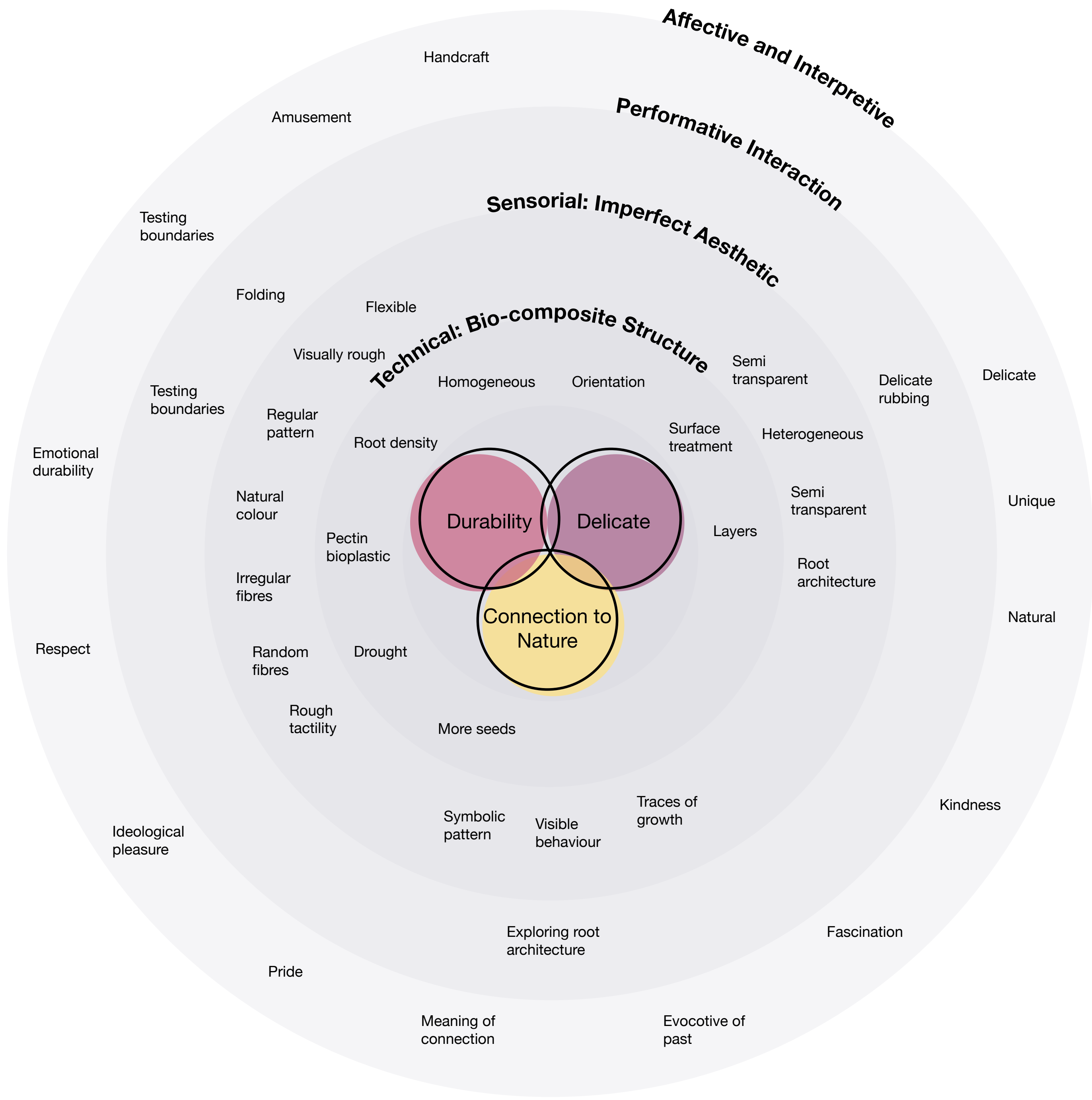


Figure 45. Main findings represented on material experience levels.

5

Experience Vision

This chapter introduces the experience vision. The material concept is introduced, material qualities are summarised and benchmarking and material trends are summarised, leading to a vision statement.

Material Concept

Introduction

The material concept is a combination of pectin bioplastic and the interwoven root structure. In this concept the roots will be grown into patterns representative of nature. Once harvested the material samples will be layered on top of each other and combined with pectin bioplastic to create a bio-composite.

Biocomposite

The pectin will act as a matrix that will provide bonding to the layering of Interwoven fibres, reinforcing the root structure. Stacking the layers should be done in a way to maximise strength with continuous fibres, orientation based on where the applied load is. With as much heterogeneous interconnectivity as possible. The layering of the sheets should create an imperfect aesthetic that becomes stimulation to evoke interpretations of naturalness, and elicit reflective emotions that give rise to evocative memories of the past. Imparting feelings of kindness for the material, creating a richer long lasting user relationship.

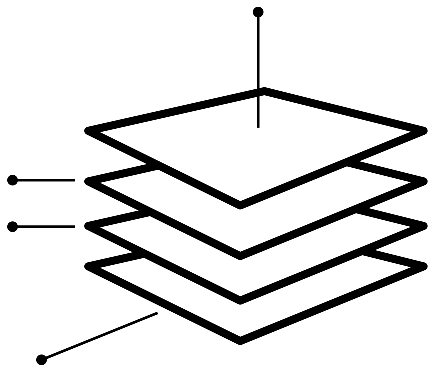
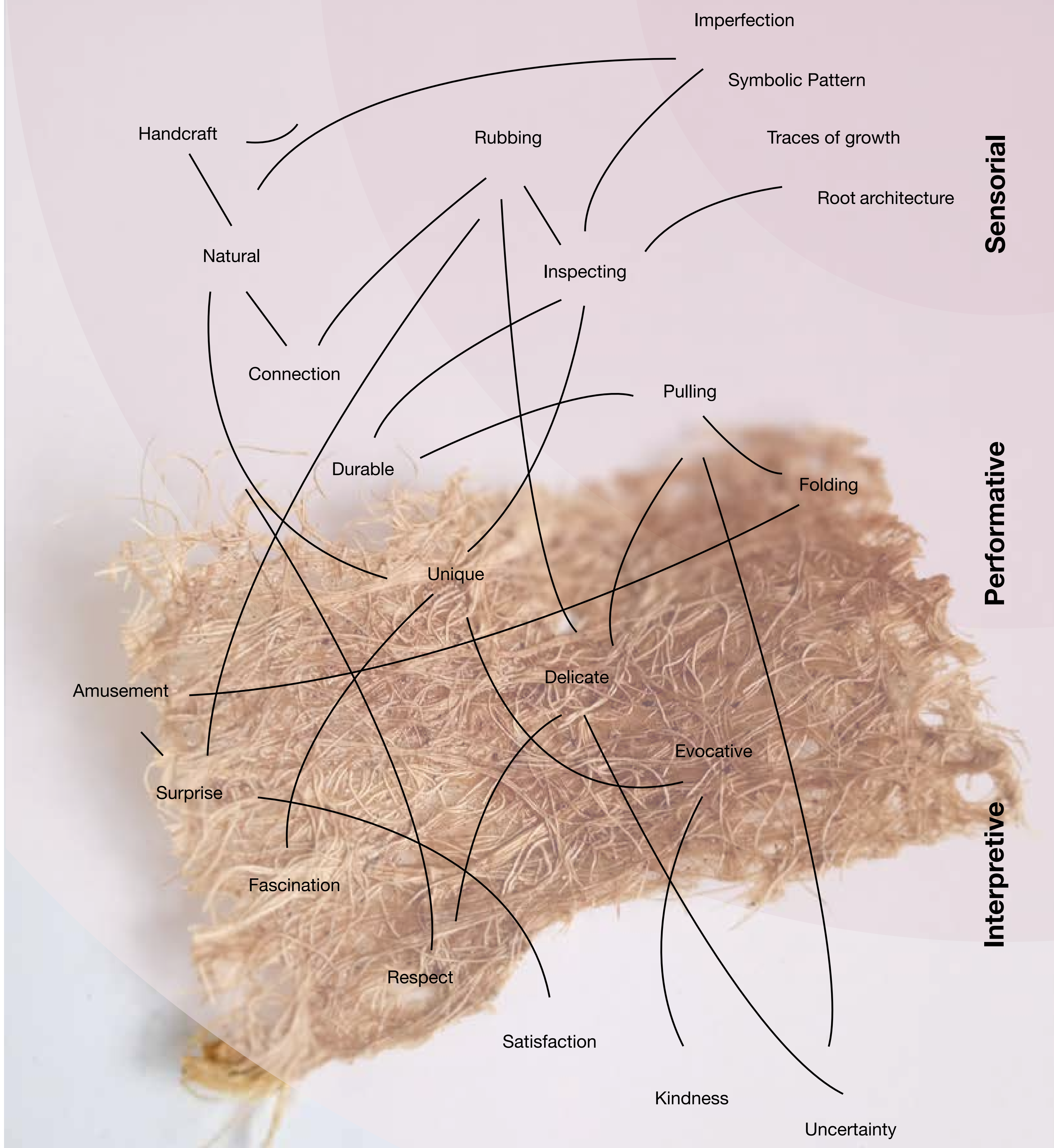


Figure 47. Illustration of stacking of bio-composite.

Symbolic Pattern

The pattern structure will be manipulated to show patterns from nature, exhibiting the collaboration of the roots and human intervention. This should Illustrate the roots affordance to be tailored into a desired form, exhibiting the roots unique behaviour during the time of its growth. This will be representative of the meaning of connection we have to nature.

Figure 46. Example of fine level of detailing possible with patterns.



Relationship of Experience

The diagram illustrates the expected relationships of the four levels of material experience for the material concept. To recap, interactions with materials can be seen as experiences (Karana, 2009). In a nutshell, the sensorial experience relates directly to the aesthetics of the material, whereas the performative experience is the way users interact with the material, affective experience refers to the feeling of users and finally the interpretive experience is how users judge the meaning.

Vision

The MDD method guides the design process when experience is the expected outcome from material properties and experiential qualities to a materials experience vision within a wider context for its purpose of existence.

Introduction

To begin concept development, the MDD method recommends to formulate a Material Experience Vision to be able produce suitable product applications. The vision represents the design goal for the material and expresses what role the material has in relation to product - user - interaction and context. Material qualities are extracted from the vision and translated into a product context with both technical and experiential qualities taken into consideration. Affective qualities and interpretive qualities come forward to elicit the meaningful experience desired.

Without the vision, general concepts evolve without using the full potential of the material (Karana et al, 2015). because idea generation intuitively emphasizes the technical material qualities and pays less attention to the experiential qualities (Ashby & Johnson, 2010). Therefore creating a Material Experience Vision ensures that both areas are equally addressed in the design of a product.

A series of questions from the MDD method (Karana et al, 2015), guide the formulation of a vision statement.

- What are its unique technical/experiential qualities to be emphasized in the final application?
- In which contexts 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)?

Qualities of material concept

This section presents two overviews from the previous chapters. They are divided into technical and experiential qualities. The overviews are based on the material concept.

Experiential Qualities

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 sensorial qualities (sensorial);
- The most and least pleasing sensorial qualities;
- Other materials it is associated;
- The meanings the material evokes (interpretive);
- The emotions the material elicits (affective);

Mapping the Findings

Figure 48 below illustrates a schematic overview that provides guidance to put materials into a perspective with other materials, context of use and a role in society. This comparison brings forward the gaps that have not yet been addressed to be translate into the material opportunities that enables the Material Experience Vision to be formulated.

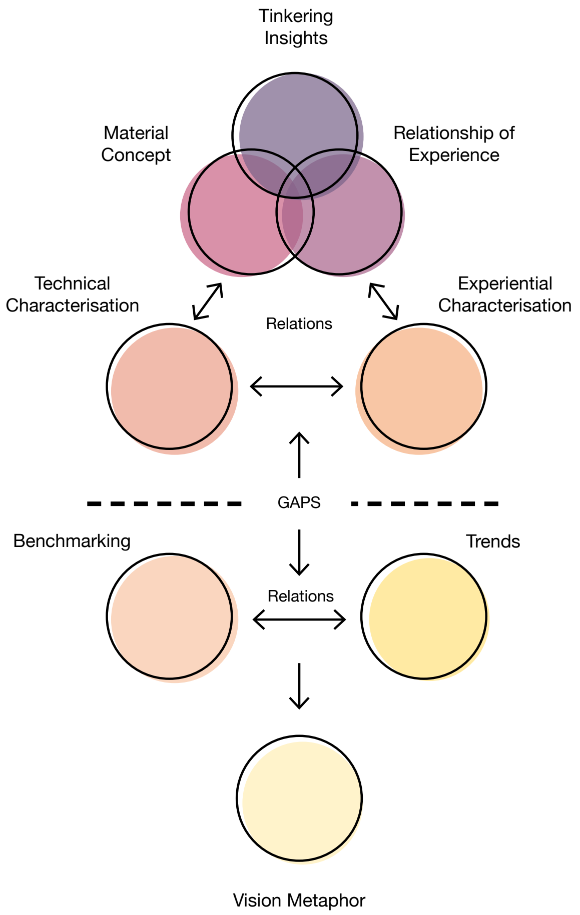


Figure 48: Vision is articulated based on the gaps between what the designer has done and what others have done

- How people interact and behave with the material (performative).

Technical Qualities

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

- Convenient manufacturing method;
- Key technical properties;
- Uniqueness of manufacturing method;
- Technical constraints;
- Technical opportunities.

The main objective of these classification overviews is to extract the main characteristics of the material, which will be compared to the benchmarks that follow in the next section. See figure 50 for the overviews to the right.

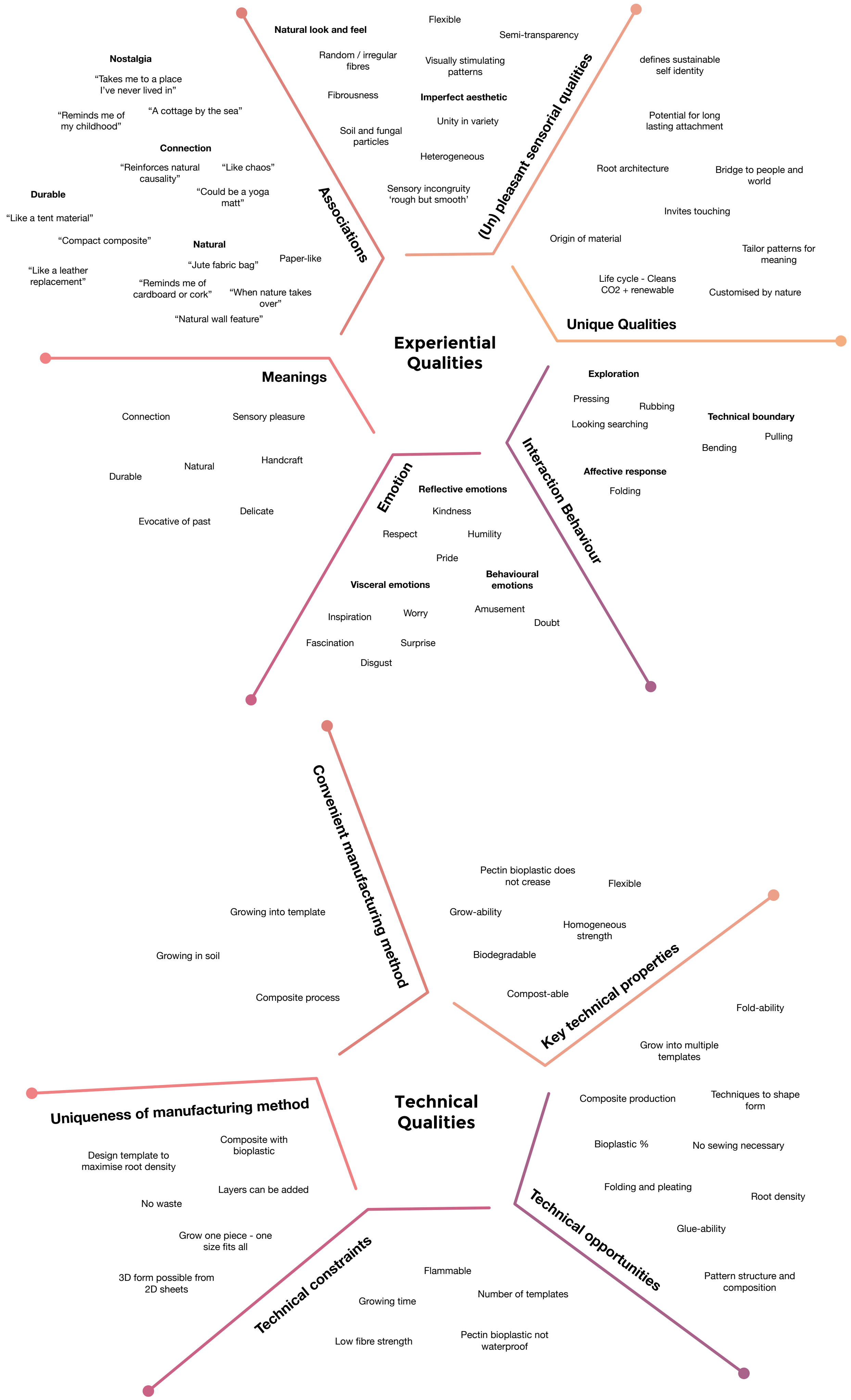


Figure 50: Illustrated overview of experiential qualities and technical qualities of material concept

Benchmarking

This section presents three benchmarking: **1.** Natural fibre textiles that exclude traditional textile processes; **2.** The phenomenon to manipulate nature and intervene in the natural state of an organism i.e. limiting the growing space; **3.** The processes used to enhance the natural materials technical characteristics with biology, composites or secondary processing.

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).

Natural Fibre Textiles

The full benchmark can be found in appendix C.

Extracting natural fibres to create textiles has been around for a long time in human history, yet recently, material developers are experimenting with new techniques besides traditional spinning and weaving. The benchmark includes both traditional and new textiles. They are categorised by the source of the raw material: *Grown, up-cycled and harvested.* Roots haven't been explored, which remains a potential for its uniqueness. Since Interwoven is a semi-developed material, this benchmarking is used to compare it to its material family: natural fibre textiles (excluding traditional textile production practices).

Applications: Textiles, upholstery, bags, book covers, clothing, wall dividers, wallets, carpets and footwear.
Activities: Protect and hold objects, cover body, functional utility, decoration, identity, styling, furnishing.
Technical properties: Biodegradable, strength, durable, flexible, lightweight, water resistant, tear resistant, anti-microbial, sew-able, grow-ability.
Experiential properties: Natural appearance, Ageing, irregular surface, unique, handcraft, leather like.
Purpose: Material as sustainable replacement, show ability to be mass produced, hypothetical future, heritage, material surrogate.

GROWN

Figure [ ]: Jacket made from growing bacteria by Suzanne Lee

Figure [ ]: Dress made of pure mycelium by MycoTex

UP-CYCLED

Figure [ ]: Wallet made by Banana Leaf Paper, Micronesia

Figure [ ]: Shoe by Ahinsa, made from Pinatex

HARVESTED

Figure 51: Cork Leather by Dan & Mez, 2019

Figure 52: Ugandan-born British designer José Hendo uses bark cloth.
PHOTOGRAPH BY GIULIO MOLFESE

Manipulated Nature
The full benchmark can be found in appendix C.

This benchmark shows examples in which human beings intervene in the natural state of growing conditions of living organisms, in order to reach a certain human goal. This area overlaps with growing design and digital biofabrication (Camere and Karana, 2018) but it emphasizes man's interventions to take advantage of a natural process to produce something. The manipulation techniques include: reforming growing space/ direction, guiding living organism with food, and giving a pre-made habitat for living organism.

Applications: Packaging, architecture, furniture, saving space, decomposition of humans, bridges, exhibitions, urban management.
Activities: Decoration, attract attention, protection, bearing load.
Technical properties: Biodegradable, strength, durable, flexible, lightweight, water resistant, impact resistant, anti-microbial, grow-ability.
Experiential properties: Natural appearance, futuristic, inspiring, provoking, temporal, adaptive.
Purpose: Material as sustainable replacement, showcasing power of nature, hypothetical future, material surrogate, archetypical sculpture.

Enhancing Natural Materials
The full benchmark can be found in appendix C.

This benchmark shows examples of current practices to enhance natural material properties by physical, chemical and biological means. Enhancement includes making the material strong, hard and tough, making the material water resistant, making the final product load bearing. Techniques of enhancement include: Growing a second skin, altering the material structure, and processing composites.

Applications: Footwear, plates, furniture,
Activities: Load bearing, protection, aesthetic attention
Technical properties: Biodegradable, strength, durable, flexible, strong, tough, water resistant, impact resistant, grow-ability, mould-able.
Experiential properties: Natural appearance, futuristic, imperfect, inspiring, handcraft, warm, tactile.
Purpose: Material as sustainable replacement, re-purpose waste biomass, hypothetical future, material surrogate.


Figure 52: Chair by Full Grown


Figure 53: Heat shaped water melon from Japan


Figure 54: Sculpture of vase made by bees, from Libertíny


Figure 55: Typography made by bacteria from Abbema. J


Figure 56: Living Root Bridges, Bangladesh

GROWN STRUCTURE COMPOSITE


Figure 57: Bacteria used as microbial weaving by Jen Keane


Figure 58: Truss Me, bamboo furniture by Sandeep Sangaru


Figure 59: Flax Chair, woven flax combined with PLA by Christein Meindertsma

Opportunities for Interwoven
Taking the benchmarks into consideration. The approach for designers to use nature as tools for materials development offers many opportunities to achieve new and unconventional materials experiences (Rognoli, 2015). The main opportunities for development are summarised:

1. Origin Story: Many products that use biomass mixed with a resin for added strength, create an imperfect aesthetic, but do not express the origin of the materials. Interwoven can be manipulated to expose the roots, and embody the story of natures craft and the biography of the roots through symbolic patterns. To create aesthetic expressions grounded on 'imperfect aesthetic qualities' (Rognoli et al., 2015) - that show the traces of life.

2. Acceptance: Since Interwoven is evocative of images, memories and feelings, a product approach can be to exhibit a utility function. So that users have to trust and depend on Interwoven. This would be at odds with other growing design approaches which often stay as hypothetical examples which are criticized for their lack of utility properties like water resistance.

3. Handcraft Expression: Exposing craftsmanship of biology or the skills of artisanal labour is brought through in many products in the benchmark, representing local identity. Interwoven can embody the story of craft and the biological collaboration. By connecting traditional practices of artisanal making with the roots.

4. Growing End products: Many of the products in the benchmarks require additional processing or tailoring to be complete. Interwoven can be grown directly into a final design. Similar to mycelium products.

Conclusion
Growing design projects are associated with a closer connection to nature due to the origin of the materials. Inherently they are more delicate due to a lack of technical utility, acting as artefacts to make people think about future possibilities. Whereas up-cycled, composite structures are more durable and accepted in market, because they exhibit utility in their use phase.

Therefore it is reasonable to say that Interwoven as a combination of both growing design and a bio-composite structure embodied in a product that exhibits utility functions would increase its acceptance and exhibit the desired qualities of durability, delicateness and connection to nature. Providing the insights from the exploring Interwoven chapter are kept.

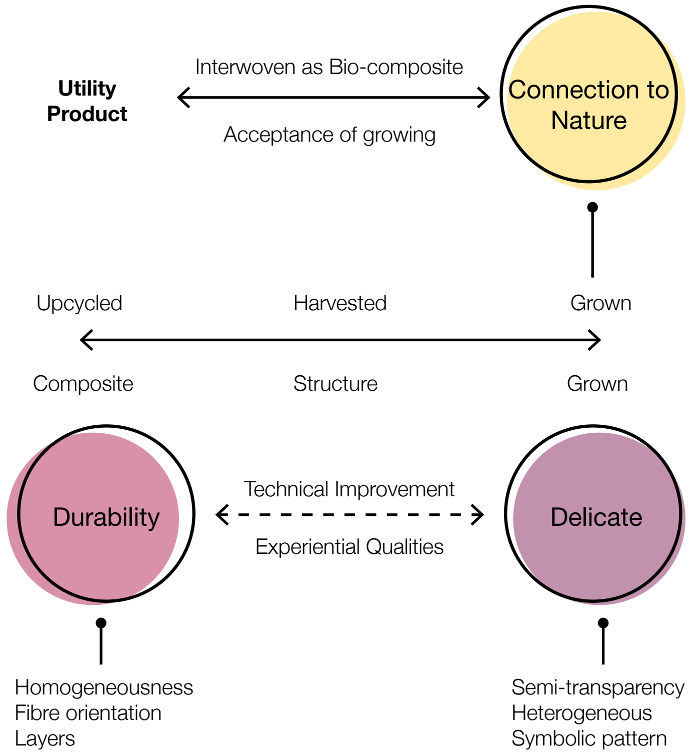


Figure 59: Illustration of concluding thoughts

Further Benchmarking

This section presents a benchmark of a product design space. That being: Natural Fibre Composite Bags. The competitors identified in the benchmarking are mapped according to a perceptual map to indicate the opportunity area. The reasoning for a bag is described below.

Natural Fibre (Bio)Composite

Interwoven has its roots in DIY practices (Rognoli, 2015) bringing a new dimension to the textile industry through its low tech approach that is utilised in a new age way. Its unique origin lends its self to be a sustainable alternative. However it still needs to be accepted by the public and designers to become a material for design. As mentioned in the previous section this can be facilitated by embodying it in a utility product to exhibit its strength as a bio-composite.

In discussion with supervisors and Diana Scherer it was decided that the Interwoven bio-composite can be a **bag**.

Acting as a surrogate application of a well known product should help manage expectations concerning function and utility (Parisi, Rognoli and Ayala Garcia, 2016). A bag can represent the strength of the bio-composite textile and connect craftsmanship with natures craft.

Empirical studies have shown that to achieve high aesthetic appreciation among consumers, designers should aim for the best combination of typicality and novelty (Hekkert et al., 2003; Hung & Chen, 2012). A typical product is often preferable to people as it requires less energy to understand it. This balance can facilitate the acceptance of the material (Karana, Hultink, Camere, 2018). Since the material is highly novel, a typical product needed to be chosen.

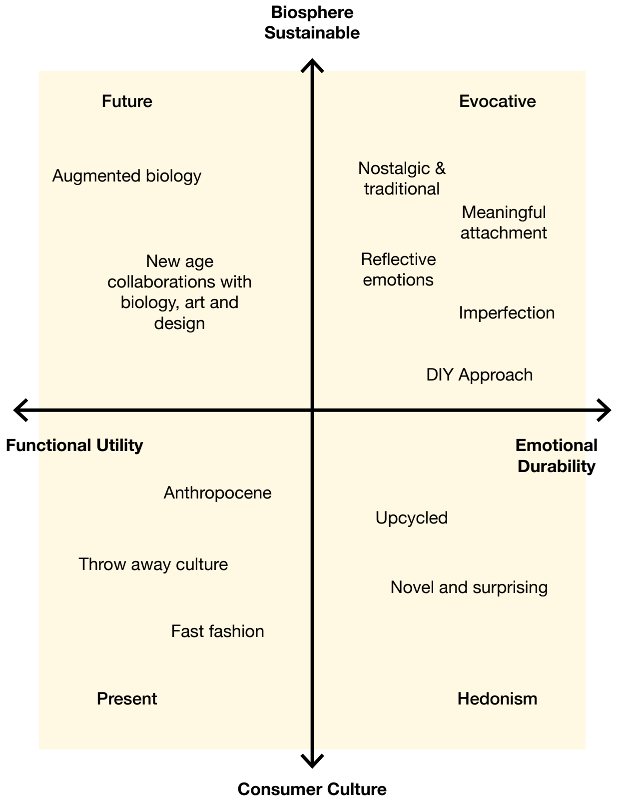


Figure 60: Perceptual Map

Natural Fibre Composite Bags

Techniques such as utilizing mind maps and clustering data onto a perceptual map was used to identify a opportunity area.

This benchmark shows examples of current developments in natural fibre composite bags. The benchmark is mapped on a perceptual map to help to confirm strategic blank spaces and support the vision statement. The perceptual map was created based on clustering data from the previous sections insights.

Applications: Bags
Activities: Load bearing, protection, aesthetic attention, carrying, signs of time
Technical properties: Biodegradable, strength, durable, flexible, strong, tough, water resistant, impact resistant, grow-ability, mould-able, sew-ability.
Experiential properties: Natural appearance, imperfect, inspiring, organic, ordinary, sober, handcraft, warm, tactile, bright.
Purpose: Material as sustainable replacement, re-purpose waste biomass, hypothetical future, material surrogate, local social enterprise.

A. Mycelium leather grown in a lab by Montalti. M
B. Fruit Leather Rotterdam
C. Palm Leather bag, by Tjeerd Veenhoven
D. Pure Mycelium Bag by MycoTex
E. Mycelium bag by Mylo
F. Leaf Leather bag by tree tribe
G. Cork tote bag
H. Paper leather duffel bag
I. ReWrap, Cocolok bag by Enkev
J. Denimx, suit case by Marc Meijers
K. Pinatex tote bag
L. Comme des Garcons PVC paper bag

Figure 61: Perceptual Map with natural fibre composite bags

Opportunities

1. Composite glue-ability: Most of the bags are composites which are then tailored into a bag, Interwoven can be grown directly into shape and then formed without any need for sewing.

2. Form and strength: Many of the bags rely on adding other materials to either add functional utility or add to the aesthetic appreciation, such as adding a cotton lining to the inside. This consumes more materials for the making process. Interwoven can be modelled without the addition of extra materials other than the bioplastic required to enhance its strength.

3. Connection to nature: Most of the bags express subtle imperfections to elicit a natural look and feel, but do not symbolically represent a connection to nature. Interwoven's untamed root system exhibit the traces of growth in a pattern representative of nature.

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.

Grow-ability as sustainability
Growing design practices such as the two by Suzanne Lee and MycoTex stand as solutions for reducing the rising impacts of climate change and the use of fossil based resources. They show the potential of new manufacturing horizons that entail working with organisms as collaborators, supporting the emergence of a bio-economy that is at odds with synthetic textile production.

They do not require the traditional chemicals, pesticides, heavy use of water and farmland needed for cultivation of traditional textiles, as only what is needed is grown with little waste during production. In this sense they are the closest to Interwoven. Although the two products mentioned act as surrogates for existing materials as a sustainable solution, they are still hypothetical examples as they are not feasible to be in production due to a lack of technical utility, such as water resistance and are difficult to scale. There main purpose is to generate beneficial environmental awareness. Acting as a design proposal to challenge narrow assumptions, preconceptions and givens about the role products play in everyday life (Dune and Raby, 2007).

Interwoven can challenge the current consumption paradigm, of the textile industry by being a textile with adiqute utility.

Up-cycled Materials
Up-cycled textiles are made through taking a biomass waste stream, usually from agriculture and processing it into a material of higher quality. They contribute to the circular economy, supporting the environment, and are socially ethical as they provide new sources of income for the regions the biomass comes from. Typically they reflect the local identity through the use of the materials, techniques and resources that are available in the areas they are produced. This is particularly clear with the Banana Leaf Wallet because it employs local Micronesian artists to decorate the designs.

As products on the market they already play an important role in setting new values in society. Influencing people's appreciation of aesthetic aspects of imperfection and the whole philosophy of sustainability (Rognoli & Karana, 2014).

They are product examples of new textile biomaterials that have successfully made it to the market, acting as surrogates to materials like leather as they exhibit similar characteristics, i.e. the Pinatex shoe. The materials require the addition of other natural materials and further processing to be usable. They all have a natural aesthetic, with some imperfections of grain and visible fibres but do not explicitly show the narrative of the material or gives hints to the origin of the fibres. This is an opportunity for Interwoven.

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 fit these materials into new models of business, such as Cradle 2 Cradle (Mcdonough et al., 2010). In order to do this, new materials requires more acceptance by both designers and consumers.

Interwoven, a balance should be made between the novelty of the material and the typicality of the product it is embodied in. Studies have shown that to achieve high aesthetic appreciation among consumers, designers should aim for the best combination of typicality and novelty (Hekkert et al., 2003; Hung & Chen, 2012).

Source: Unsplash, Josh Marshal

Social Trends and Issues

In addition to the material benchmark and material trend summary, towards supporting the Material Experience Vision, it is necessary to look at the role the material can play in society and if it can complement current trends as well as address societal issues. The better the material fits in the current trends in society, the more likely it will reach widespread adoption.

Extinction Rebellion:
The momentum of post industrialisation has brought us to a collective awakening of our impact on the planets capacity to sustain life. The level of our unconsciousness is being reflected back at us through biodiversity loss, pollution, climate change, and resource depletion, problems we all face together. Its no wonder that protests like Extinction Rebellion - a global environmental movement aimed to compel government action to avoid tipping points in the climate system, biodiversity loss, and the risk of social and ecological collapse. (wikipedia). They have even called for a boycott of the textiles industry, asking people to not buy clothes for a year. A result of the textiles industry being the 4th largest polluter in the world after food and drink (European Commission). Coupled with a fashion industry being a major catalyst for over consumption of goods that are being produced and used for just a short time period due to a throw away culture mentality. Is putting strain on natural resources and increasing the amount of waste and pollution in our biosphere.

Where can textile lovers get their fix?

Sustainable use of materials needs to be addressed if we are to realise the vision in the Brundtland Commision Report, Our Common Future, 1987. Designers play a role in determining the environmental and social impacts of materials. The emergence of economical models has modified over time from design for sustainability, cradle to cradle (Mcdonough et al., 2010), circular design, product service system and more recently an emerging organism industry (Collet, 2018). With more than 50 countries integrating bioeconomy into policy strategies. (Global bioeconomy summit, 2015, p4).

The evolution of 'biotextiles' is an emerging material practice for the bioeconomy and those textile lovers. It supports aligning our production models with new approaches that sustain equilibrium with the natural world that we depend on to survive (Collet, 2018). It is part of the circular design model that needs designers act through biodesign (Myers, 2012) and collaborate with biological production to support the transition towards a more sustainable future.

Diana Scherer with Interwoven has created an unprecedented new textile that is part of this transition and is characteristic of a research approach of exploration with an organism in making textiles, as mentioned in the Materials Trend Summary. This highlights its compatibility with trends in society.

Vision

The material experience vision is based on users studies, material concept, material benchmarking, material trend summary and social trends and issues. Summarized into a coherent whole in order to bring about relevant and critical issues and to define a unique and meaningful vision.

During users studies it became clear the imperfect aesthetic of the samples elicited evocative images, memories and feelings that were representative of our close connection to nature.

The naturalness of Interwoven is grounded in 'imperfect aesthetic qualities' (Rognoli et al., 2015) that showcases the traces of life, which become active stimulation for cognitive, affective and performative processes. Particularly the reflective emotions that give rise to feelings of kindness for the material. By eliciting care towards its delicate nature coupled with the uniqueness of the root architecture, this stands as a strategy for emotional durability (Mugge, R et al., 2008) to create rich and more enduring relationship (Rognoli & Karana, 2014). The rich material experience can lead to longer attachment as it represents ones values of sustainability leading to ideological pleasure (Jordan, P.W, 2000).

Designing a bag to embody the Interwoven bio-composite will help manage expectations concerning function and utility and represent its strength, connecting craftsmanship with natures. It was noticed that people found the root system fascinating to explore and satisfying to touch and so these experiential qualities can be utilised for a positive tactile experience.

Photo by John Kakuk on Unsplash

Thus a Material Experience Vision is created:

I want people to trust the interwoven 'bio-composite' by designing a bag to represent its strength and exhibit the delicate root architecture through artisanal craft, bonding the wearer to a deeply evocative connection to nature.

6

Material Development

This chapter introduces the material development towards creating a durable yet delicate bio-composite textile. A study on patterns, and further technical tests are presented.

6.1 Patterns

A unique aspect of the roots is that it elicits deep connection to nature in a tangible way and since it is possible to grow the roots into any desired pattern, a decision has been made to research patterns that are ubiquitous in nature to realise and enhance that emotional connection and interpretation to natural.

Natures Artistry

There are patterns all over nature and the way these patterns are created tells a story of progressive division and subdivision of physical forces that create the diverse forms of animals and plants. Life on Earth shows a bewildering variety of shape, form and pattern again and again in places that you'd think have nothing in common, like how a river net works resemble our veins and arteries or slime mould resembles the bottom of a Maple leaf.

It is a fractal nature, meaning they are objects in which the same patterns occur again and again at different scales and sizes. In a perfect mathematical fractal – such as the Mandelbrot set (figure 62) – this "self-similarity" goes infinitely deep: each pattern is made up of smaller copies of itself, and those smaller copies are made up of smaller copies again, forever. Many natural phenomena are fractal to some degree, below are images that show fractal nature figure 62.

Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry.

Richard Feynman

6.2 Pattern Types

Patterns can be organised in certain arrangements consisting of a certain organisation and style of individual forms. These arrangements make it possible to classify patterns into different pattern types.

Patterns typically extend in space as they go on and on while form is bound and finite, but it is the organisation of these forms that can create a pattern type. A pattern has a form in which particular features recur recognisably and regularly, identical or symmetrical, may have repeating elements that are similar but not identical, that can repeat in a way that is regular but without following perfect symmetry and is temporal. Such as the ripples in sands from windswept deserts. Patterns then are created from group features, which is why patterns can be recognised in places that are irregular in structure, like the peaks of mountain ranges.

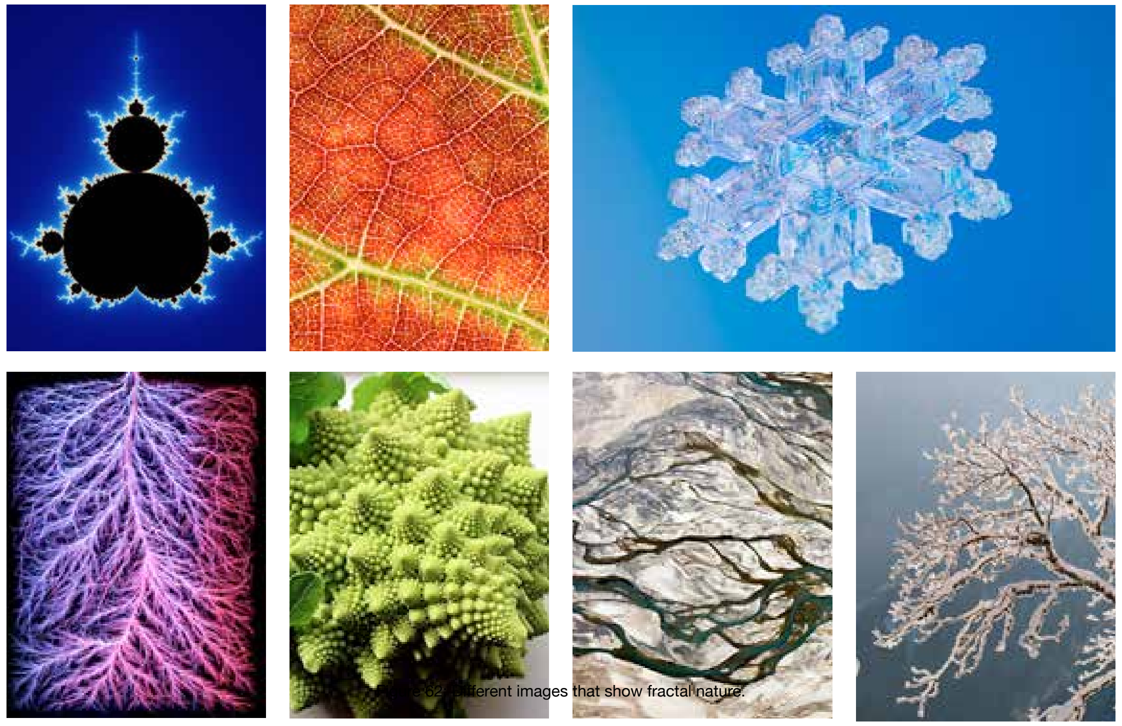


Figure 62: Different images that show fractal nature.

Left to right top row:
1. Mandelbrot Set
2. Network of veins inside a leaf
3. Sixfold symmetry of this snowflake

Left to right bottom row:
5. High-voltage electricity discharge through acrylic sheet, known as a Lichtenberg figure
6. Romanesco broccoli
7. Braided glacial river channels
8. Sycamore, a central trunk forks into two or more branches

Credit:
2. Paul Oomen / getty
3. Ian Cuming / getty
4. Photo Researchers / getty

In his three-fold book series *A Tapestry in three Parts*, science writer Philip Ball explains there is 'no grand theory of pattern' and that nature constructs the most intricate patterns, through complex physical and chemical processes.

He argues in his epilogue that *"What nature uses is not a law of pattern, but a palette of principles."* (Ball P., 2009 p.180 Branches). These principles or patterning processes are found working in many different instances in nature. Each pattern type follows its own set of principles, that can be boiled down to a set of rules.

Ball divides patterns in nature into three main themes: *Shapes, Flow and Branches*. For the sake of overview, this will provide the outline for the categorisation of pattern types. In order to view the research on the specific pattern types and the way in which they occur in nature, see appendix D.

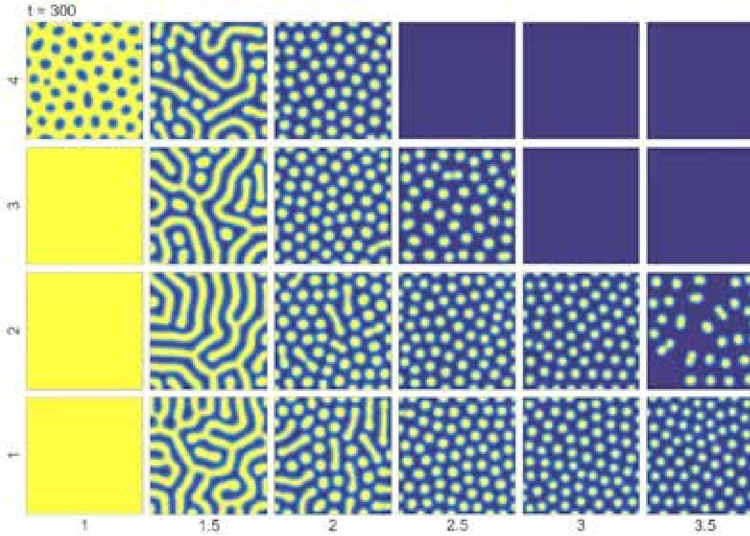


Figure 63: Generated spacial Turning patterns, sourced from youtube, by kjpainter, 2015

Reaction - Diffusion

Reaction Diffusion systems represent one of natures most widespread and versatile processes for producing patterns.

Its possible to generate *Simple Turing Patterns* based upon the *Gray Scott Model* of reaction diffusion, which simulates two virtual chemicals reacting and diffusing on a 2D grid that generates spatial patterns from almost uniform initial conditions, see figure 63. For this research, reaction diffusion patterns have been chosen because they underlies many natural processes and exhibit aesthetic principals that can be used to draw attention, such as the puffer fish in figure 65 and the figure 64. The use of open sourced online simulators have been utilised to tinker and explore with, developing patterns that mitoses from Turing patterns to Voronoi-like foam.

Below are the links to the online simulators:
1. http://mrob.com/pub/comp/xmorphia/ogl/index.html
2. https://pmneila.github.io/jsexp/grayscott/

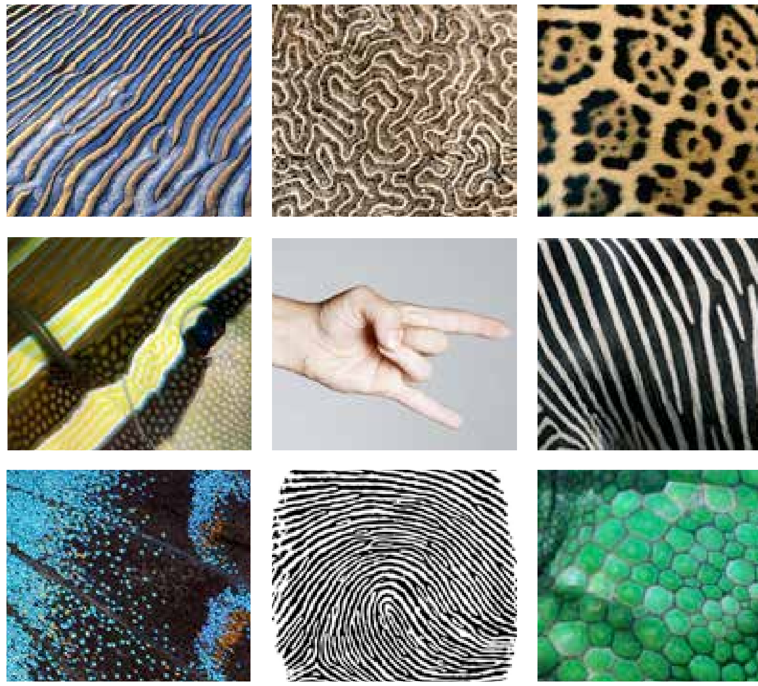
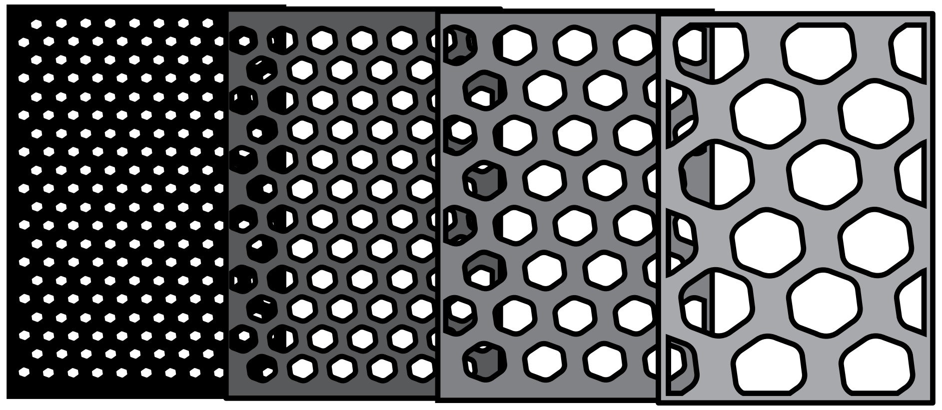
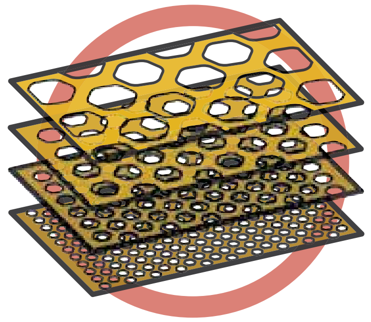


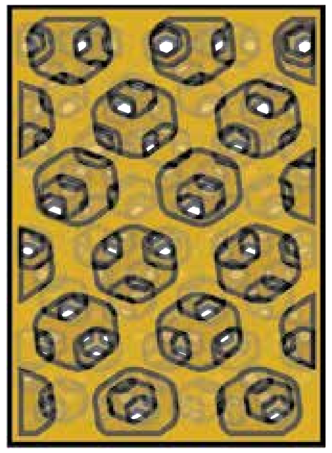
Figure 63: Images of different examples of reaction diffusion patterns at different scales

The pages show the development of patterns towards creating an aesthetic that will enhance the experiential connection to nature in the material Interwoven, while also considering the technical characterisation of the root structure and to keep mechanical stability and be perceived to be durable yet delicate.

Figure 65: Spots and stripes on a Mbu Pufferfish (FlightTravels, 2016)

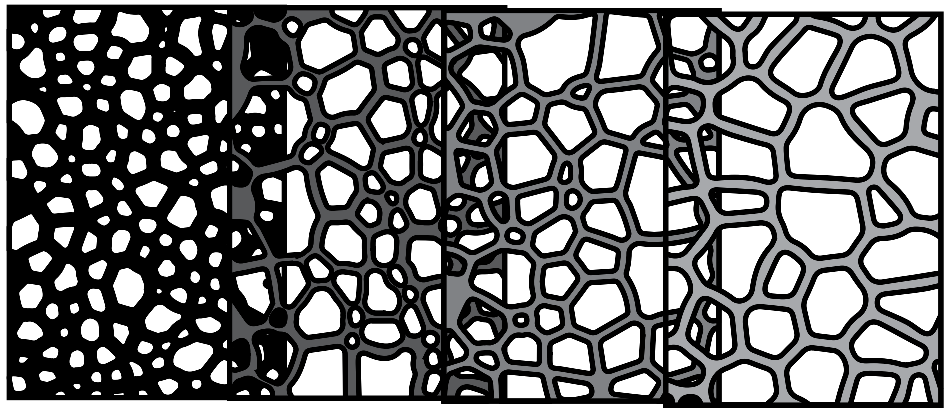


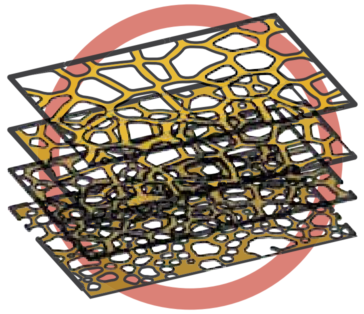


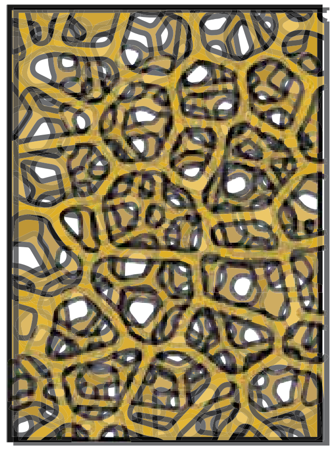


1. Honeycomb

Monodispersed
The honeycomb pattern made of many equal bubbles of a uniform size and form, creating a dispersed lattice structure of regular geometric order that is symmetrical and balanced, packed together in an identical and constant tessellation of polygonal uniformity.

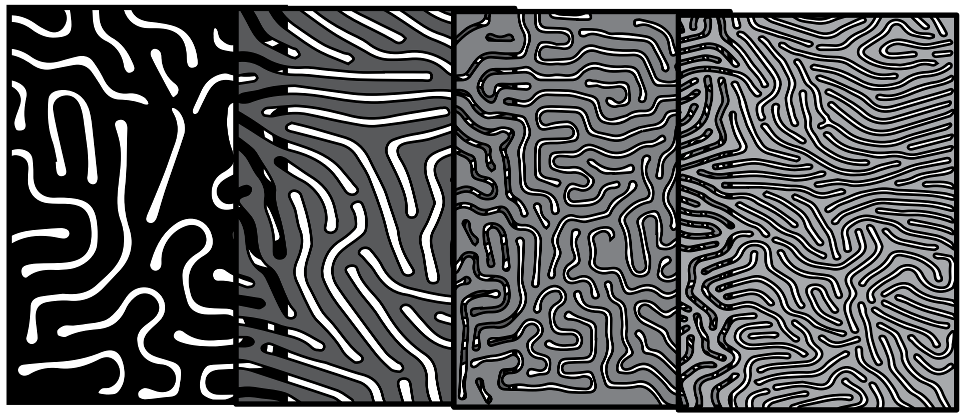


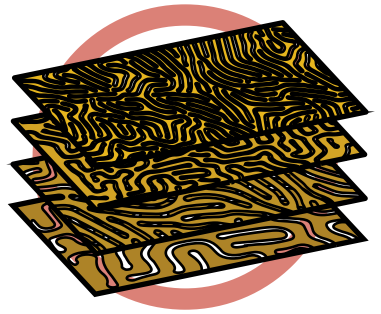




2. Foams

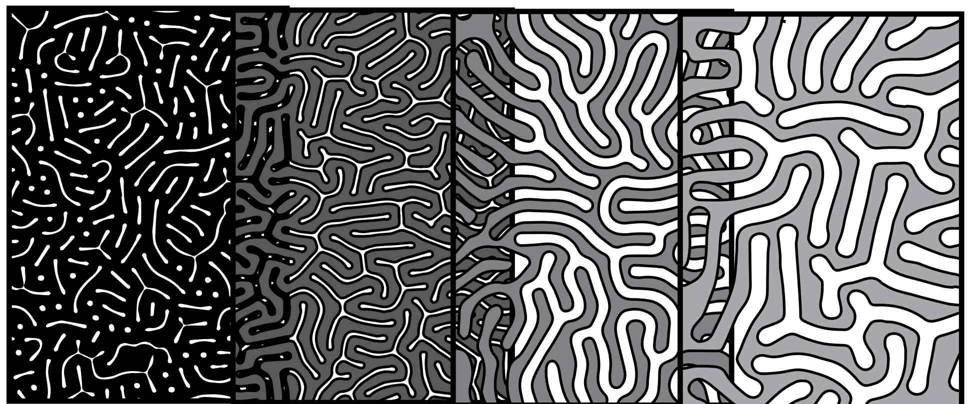
Polydispersed
Foams retain geometric regularity is becomes disorderly, lacking obvious organisation, have an inconsistent size, shape and distribution, being non-uniform. The random and haphazard cellular-like arrangement of unequal structure, sits more or less at even distances apart and with round edges.

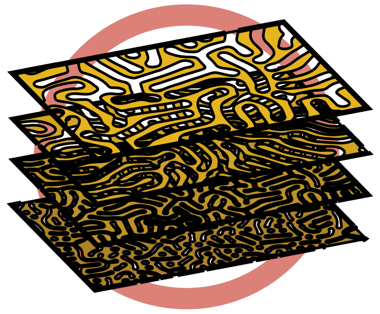


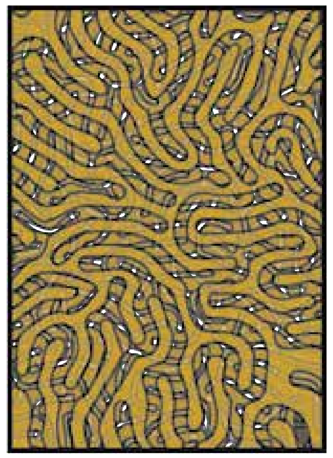


3. Stripes

Stripes have a succession of meandering and flowing lines that are irregular shapes, evenly spaced and repeating in organised identifiable directions. Each form is similar, but not identical and repetitively changes randomly in a seemingly disorderly way that has little regularity as the trajectories mutate. They lack symmetrical structure.







4. Labyrinth

Labyrinth pattern can be described as a succession of meandering lines with a little more regularity to the shapes which are branching and are evenly spaced and repeating. Each form is similar, but not identical with in-consistence size and shape and repetitively changes randomly in a dispersed and disorderly. They also lack symmetrical structure and illustrate higher entropy.

Figure 66: Grow set up in room

6.3 Pattern Development

The patterns types on the previous page were grown and added with pectin bioplastic. The results are shown and discussed.

A balance needs to be found between delicate and durable because it is desired that users interact with care and delicacy towards the material. This is initially elicited by the root architectural biography, but also the layering of the pattern structures exhibit holes in the imperfect aesthetic. In user studies this evoked delicate performances in the interaction because of the uncertainty in its technical boundaries and unfamiliarity with the material.

The visible layering of the heterogeneous pattern structures create a more homogeneousness to elicit the perception of durability. The advantage of layering the pattern structures is that regular and ordered patterns can be used with less ordered and random patterns on the top layers. Retaining the imperfect sensorial quality and balancing visual stimulation that creates order in chaos, while retaining perceptions of durability through the visible layering.

As a whole, the different pattern structures come together to create a quality to valorise imperfection (Rognoli et al., 2015) as an appealing aesthetic. On first impressions the pattern might not give rise to any recognition in the user, causing intrigue and stimulate the user to discover its unfamiliar identity or purpose. This ambiguity becomes active stimuli for users cognitive and affective responses because resolving ambiguity not only activates processes of meaning attribution but also affective processes pertaining to aesthetic appreciation and emotions (Ozan, 2016). Creating deeper meaningful experiences between the material - product - user interaction.

Figure 67: Picture of roots before being harvested

Insights from Harvest

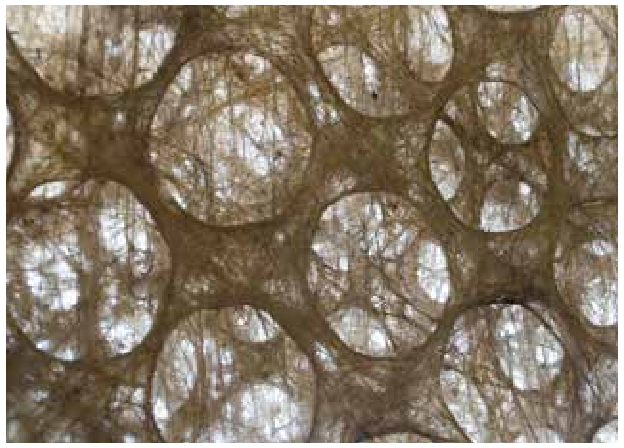
1. Root stability:
The hexagon patterns were easier to harvest as they stayed secure. Thin random meandering lines moved a lot when harvesting, making them difficult to manage. On the other hand patterns with larger form were stable as well.

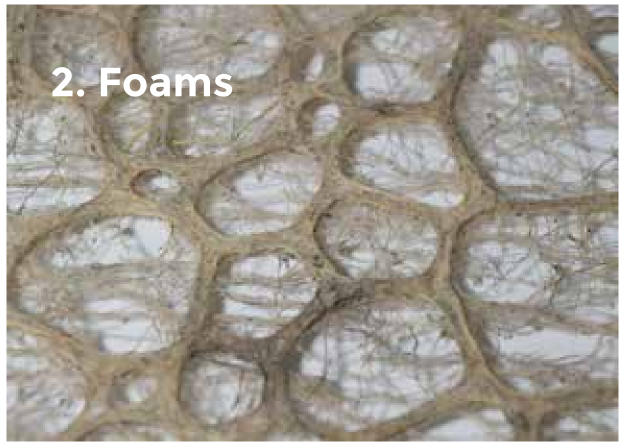
2. Thin edges: Patterns near the edge of the growth had thinner edges due to less roots being present. A note for the next time is to apply the soil over the edge of the subterranean templates.

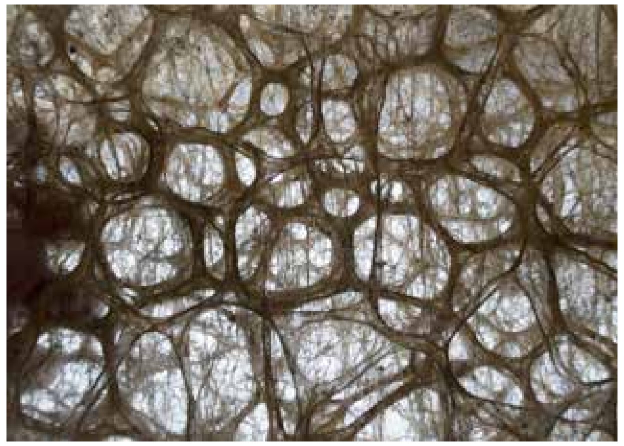
The next page shows the result of the grown samples with and without bioplastic, followed by a look at the technical properties.

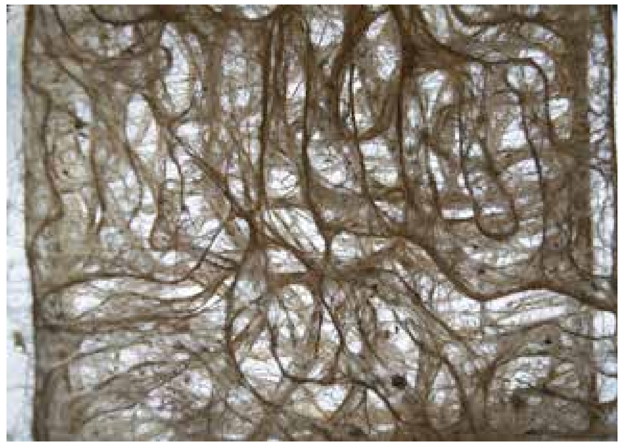
Insight

1. Pattern recognition:
Certainly when the patterns are stacked on top of each other they have an imperfect aesthetic that is stimulating to explore. On the other hand it is not immediately obvious to see the layering between the roots without holding the samples up to the light. It is easier to distinguish the difference in the layering between the hexagon and the foam patterns because they exhibit more regularity and its easier to make out the structure as a hole. This is less obvious when looking at the random irregular patterns of the stripes and labyrinth. Patterns with a wider width are more obvious than a thinner width, showing that they stand out.









6.4 Bio-composite

The patterns types on the previous page were grown and added with pectin bioplastic. The results are shown and discussed.

A balance needs to be found between delicate and durable because it is desired that users interact with care and delicacy towards the material, sensoial qualities such as semitransparent, heterogeneous with an obvious symbolic pattern are qualities for delicateness. It is experimented with different layering to explore the effect of the Interwoven sheets with the pectin bioplastic. The figure below acts as a reminder of the qualities required. From top to bottom the layering is as follows: *1. Two layers, 2. and 3. Three layer and 4. Four layers.*

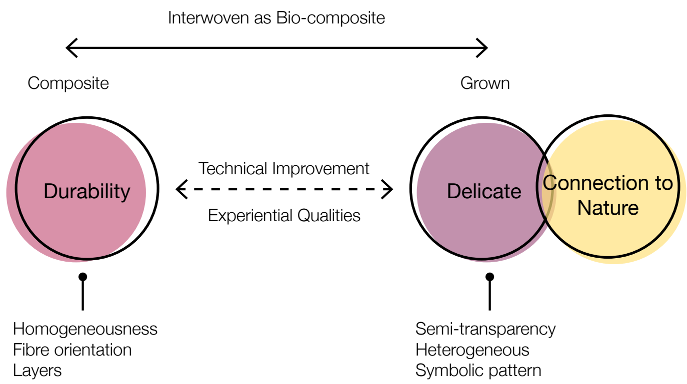


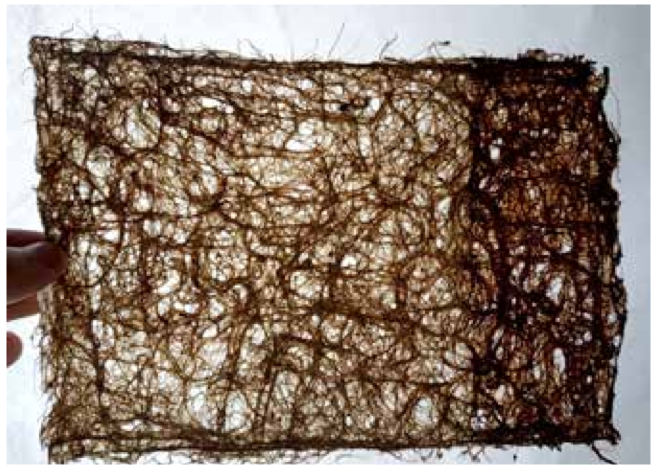
Figure 68: Experiential qualities required

Insights

1. Patterns disappear:
The patterns disappear almost entirely when made into a bio-composite. Patterns with thin cross section are visible but only when you take a much close look at the surface. Therefore the symbolic pattern placed on the surface of the bio-composite should have a thicker cross-section to show contrast from the below layers.

2. Focus on strength:
Since the patterns are not obviously visible in the layering, the focus should be on creating a fibre orientation that is continuous to maximise strength for the bio-composite. This is explored in the next section.

3. Heterogeneous Vs homogeneous quality:
The heterogeneous quality is only apparent when held to the light, while when on a solid surface it seems homogeneous. This is an interesting balance of the two qualities required for perceptual delicacy and durability.



6.5 Bio-composite performance

The roots show some affordance potential in the processing and performative effects after the pectin has been applied. The insights are described below.

1. A unique feature of the bio-composite is it can be squished and squeezed tight. Upon releasing the pressure the composite will return to its original position.

2. Roots can be folded easily and manipulated into a form. A handle was made out of some random homogeneous samples (figure 69).

3. 3D forms can be made after the bioplastic has cured a little, see figure 71 for a picture of a bag made of Interwoven layers.

4. Pectin acts as a glue, making it possible to combine separate pieces together.

5. Not heat is required to cure the bioplatic.

6. Pectin becomes slimy when in contact with water. Water resistance is required.

7. Effective water resistance is achieved with a beeswax and carnauba wax combination.

8. Additionally silicone and turpentine can be used but this adds more unsustainable materials to the composition.

8. Dyeing the roots is possible when the bioplastic has been added. Using henna works to turn the roots darker brown.

Figure 68: Bio-composite being squeezed and then released

Figure 69: Handle made out of Interwoven samples

Figure 70: Adding henna to the roots

Figure 71: Bag made with Interwoven

6.6 Technical properties

The strength and structure are most relevant technical aspects of this investigation. Therefore, a tensile has been conducted.

Method

The test takes reference of Standard ASTM D5034-09 (Standard Test Method for Breaking Strength and Elongation of Textile Fabrics). However, the test method is adjusted to suit the available materials. The dimension of test specimen is adjusted to 35mm wide by 130mm long. The elongation rate is set at 2mm/min to ensure slow change in load. The failure criteria is 10mm of standard travel constant for all samples, as maximum extension. The test provides a basic idea of the load bearing ability the composite material. Therefore the differences from the standard is accepted.

Samples

Four groups of materials are chosen for the test: Two are single sheets with pectin bioplastic, one being a hexagon structure and another being linear structure. The other two samples differ in that they are two layers with bioplastic, one with a hexagon and linear structure and another with two hexagon structures. Admittedly, the 5 samples of the same group are not identical, because of the randomness of the roots autonomy during growth. Prior to testing, the samples were accurately measured (weight, length, width and thickness to ensure a proper comparison.

Results

The units of force are a vector quantity; its units are in Newtons.

The tested specimens show varied tensile strength (figure 76 & 77). The test results show that the average tensile strength of a single layer with linear roots was 80.5 N, while the single layer of a hexagon structure was 25N. With two layers, the linear and hexagon sample was 71.2 N and the double hexagon was 60.2 N. To see the table of results please see appendix D.

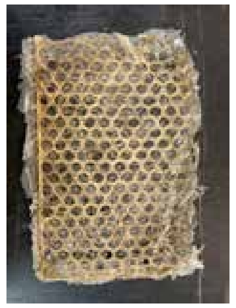


Figure 72. Single hexagon

Figure 73: Double- hexagon and one linear (Back and front)

Figure 74. Single Linear

Figure 75: Double - two hexagon layers (back and front)

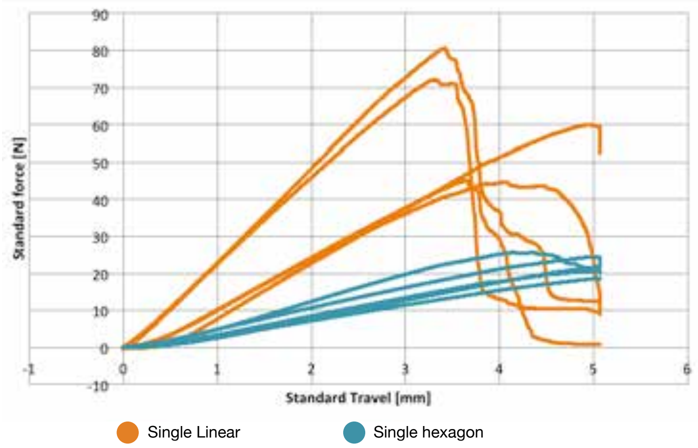


Figure 76: Stress Strain graph of single layer hexagon and linear biocomposite

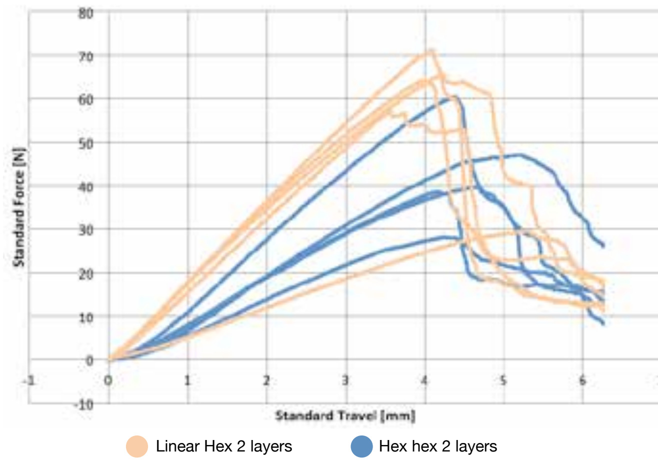


Figure 77: Stress Strain graph of two layers linear hexagon and two hexagon-bio-composite

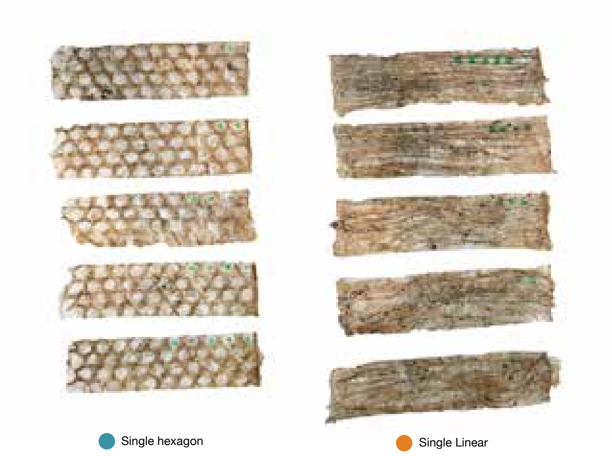


Figure 78: Samples used for the single layer structural test

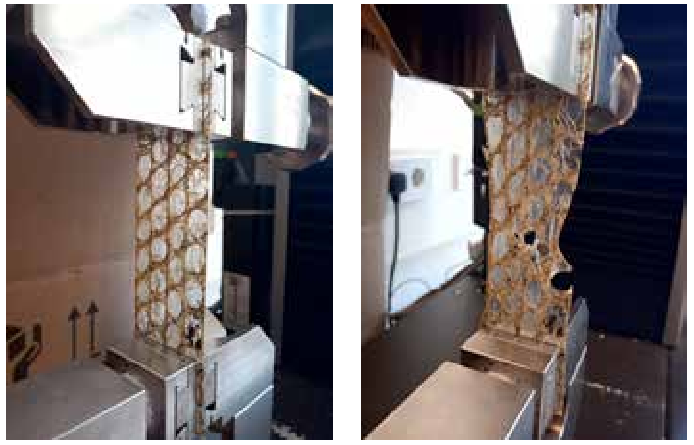


Figure 79: Hexagon samples being tested during and after failure

Discussions

The results do differ in their values, this is because they are dependent on several variables, which influence the measured results directly. These include the material production method, the material composition, microscopic imperfections, temperature, thickness and density. For this reason, the diagram of each tensile test is slightly different. The same recipe was used for each material sample by painting the bioplastic on and pressing, it does not determine an even matrix throughout the samples. Additionally it is not a fair comparison between the single and double layers. This is because the size of the holes between the hexagons increases in size in the double layers, as seen in the previous section, with more than one variable changed.

Graph 1 (figure 76)
The properties of a composite are determined by the orientation of the fibres. We saw in an earlier test that the fibres for the random homogeneous Interwoven sample is around 35.5 N, (3.2MPa). Comparatively the strength has increased with the addition of pectin bioplastic, by arranging the fibre direction in a continuous linear way. This can be due to the pectin bonding well with the roots and stabilising and reinforcing them, as demonstrated in the previous microscopic examination. Looking at the graph it is clear there is no plastic deformation as the samples decline after the tensile strength peak.

The single layer hexagon bio-composite has a much shallower slope compared to the linear sample. This indicates that the linear sample is more stiff and the hexagon sample is more elastic. This is supported by the longer standard travel of the sample.

The test has been done in one direction only, a continuous linear fibre orientation has higher strength, as seen in literature. However it would be safe to assume that the strength would be very low if the force was perpendicular to the fibre direction. Whereas it is predicted the hexagon samples would have a comparatively similar structural result, exhibiting isotropic strength.

Graph 2
The second graph (figure 77) shows that the linear direction with a hexagon has greater strength than two hexagon patterns, showing similar behaviour to the previous insights. The graph has a step configuration after tensile strength. When observing the sample it was noticed that the linear fibres break first (due to being so thin), creating a drop in the slope. The slope then continues before dropping again, as the force was distributed onto the hexagon structure. This suggest the addition of a hexagon pattern should support the composite if some linear fibres are to fail.

Takeaways

When stacking the bio-composite for a bag design, continuous fibres in two directions should be used as well as with a hexagon structure for the addition of isotropic strength.

We know that the strength depends on the density of the samples and the bonding of the bioplastics to stabilise the roots structure. The mechanical properties are likely to vary depending on the proportion of fibres and matrix, as well as the orientation of the fibres themselves. Therefore the strength of the linear fibres would increase further if they were thicker and had more interconnectedness between the fibres. This would also support a smoother harvest of the samples, keeping them together and making sure they do not meander when adding the bioplastic.

Variables, which influence the strength, include the material production method, the material composition, microscopic imperfections, temperature, thickness, fibre orientation and density.

Density was not measured in this test, however it should be added that when making the bio-composite for the bag, pressure should be applied to increase the fibre density.

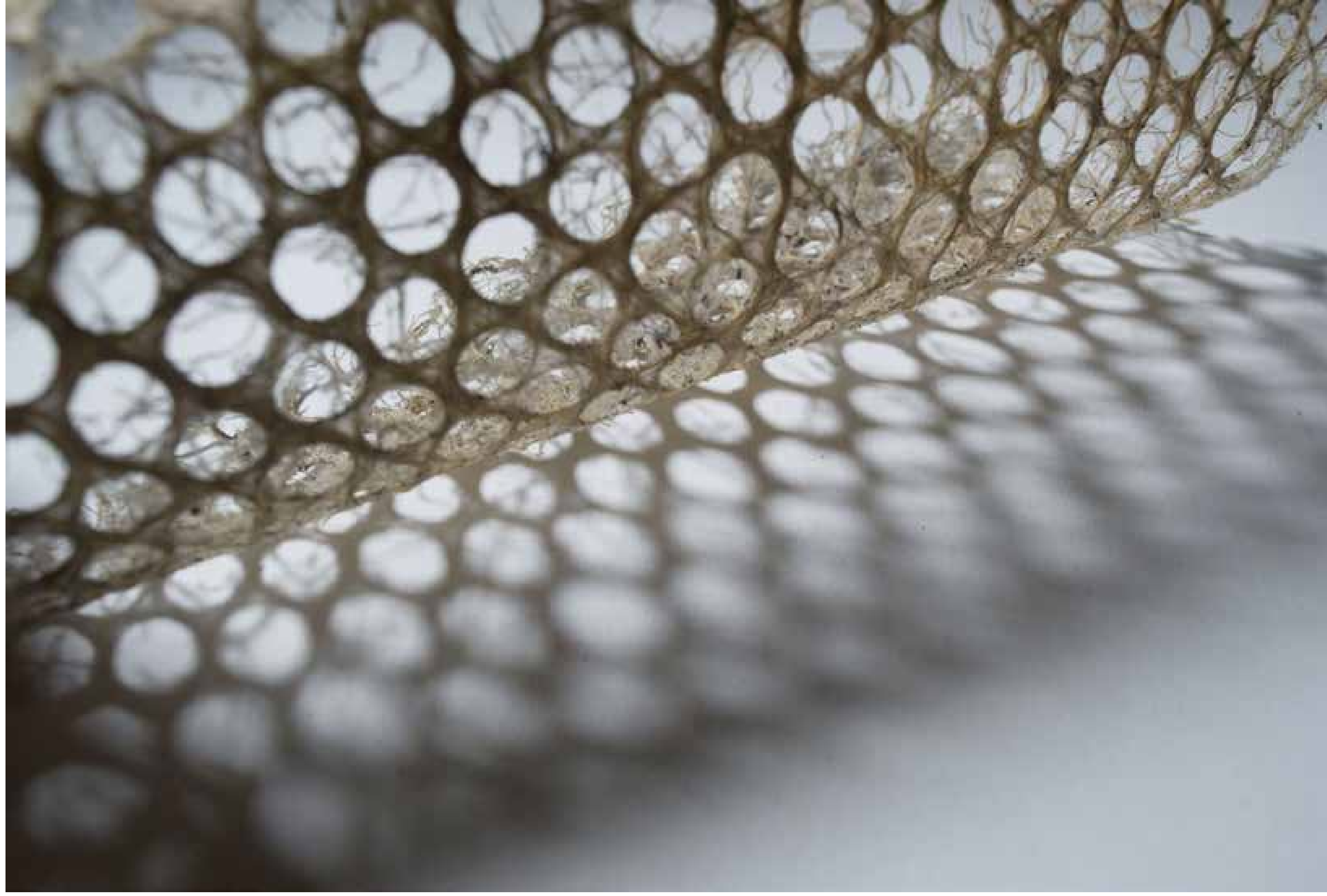


Figure 80: Hexagon sample before adding bioplastic

6.7 Conclusion

Taking the technical properties, performance and layering into consideration.

Strengthening the Roots
The strength of Interwoven has been increased, but compared to cotton it is still weaker. However, there are methods that can be utilised to increase the strength by stacking the layers of interwoven with continuous fibre orientation with a hexagon arrangement too. The linear patterns should be redesigned to have more interconnections at a cross-sectional area to ensure a greater amount of root hair connections. Previous tests showed that tensile strength with a higher density and random homogeneous inter-weaved root architecture will be more advantageous for increasing strength. This can be further increased through pressing.

Delicate yet Durable
A balance is found between heterogeneous and homogeneous, depending on the light conditions.

Water Resistance
Wax can be added to the surface of the bio-composite to create a resistance to water and also improve the smell of the material.

7

Product Concept

This chapter introduces the product concept.
It describes the prototyping, concept selection and materials experience patterns

7.1 Sketch Ideation

On the basis of the vision statement this section describes the design of a product with the material concept for Interwoven and addresses the translation of the material into a product taking into account its qualities, opportunities and design purpose.

Introduction

As a start open sketch ideation on bags was done to explore different forms that might be possible with the growing process in mind. At this stage the experiential characteristics are not specifically taken into account to ensure a sense of open creativity.

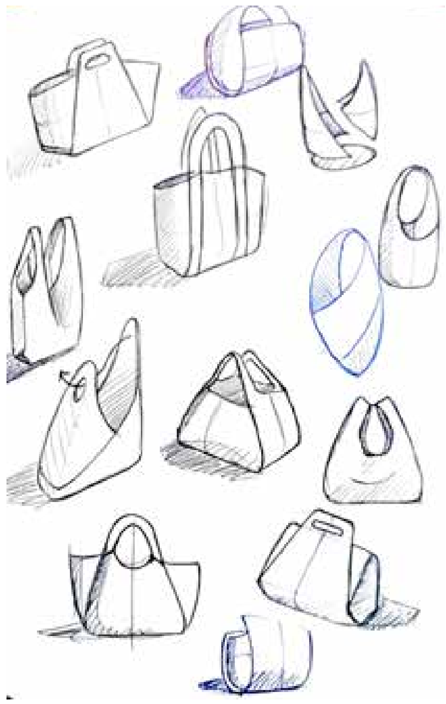


Figure 81: Sketch ideation

Inspiration

As a source of inspiration, the work of:

1. David Telfer's, duffel coat, 2010 because of the zero-waste concept that refers to fashion design that integrates pattern cutting in a way that no fabric is wasted in the making of a garment.

2. Karin Vlug's "one square fits all", which consists of 90° angles only, where no sewing is neccessary.

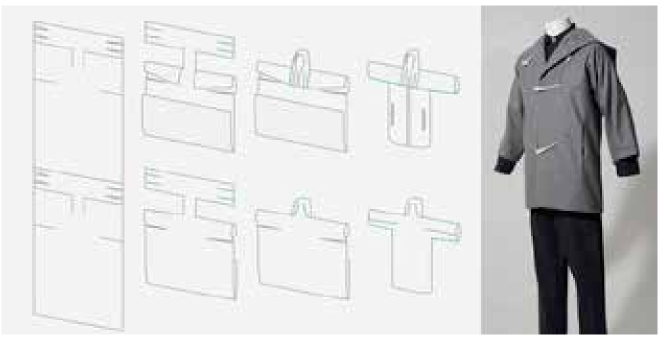
3. Bento origami bag.

Each piece has a focus on minimising waste and utilising all of the material used in a unique crafting way that develops the form of the garments. They fit well with the process of growing a single sheet and then crafting the harvested root textile with the addition of a bioplastic into the desired form.

The challenge with Interwoven is that it requires layers of material, plus the bioplastic into order to reach a desirable strength. Therefore the focus of the prototyping is on fold-ability of a single sheet to meet the required layering needed for strength, while still retaining an aesthetic that is in line with the experiential qualities of the vision.

An example of a Japanese origami bento bag

Karin Vlugs, graduation collection made only with folding and no sewing



Zero-waste garments by David Telfer, 2010. Photograph by Thomas McQuillan, courtesy of David Telfer

7.2 Prototyping

This section introduces the prototyping phase starting with low fidelity paper folding which produced two directions.

Directions

Two directions were identified that incorporated both concepts of one size fits all and origami making. The exploration with paper made for quick and rapid iterations for form development. Ultimately paper is not very close to the way Interwoven would fold and be worked and so a tissue paper material was acquired as this had closer properties to Interwoven. The two design directions are summarised with this material on the next page.

Feasibility of making

The development meandered from very simple shapes to more complex shapes and ultimately back to a simplified version. Simplicity of making was a driver for design feasibility when considering the folding and glue-ability of applying a bioplastic to Interwoven. The concepts below are described followed with schematic diagrams of the plan layouts.

Direction 1: This was heavily inspired by the bento bag formation as the principles of folding squares across the middle from top and bottom corners are the same. The difference is the conception of adding layers to add the strength in the desired locations, particularly the bottom and the sides. The advantage is that a unique form is developed with visible layering and craft signs, but the method of folding does greatly reduce the size of the bag, meaning a large piece of material would have to be grown.

Direction 2: This is a simpler method that allows for larger designs to be made, the biggest difference is the way in which the handles are formed. They are folded into each other, glued and folded again for added strength.

Below are the examples of the paper prototyping development.

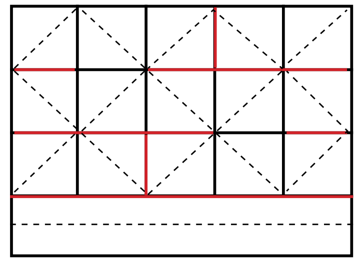


Figure 82: Illustration of 2D template to make 3D form

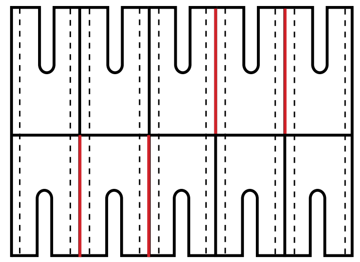


Figure 83: Illustration of 2D template to make 3D form

Direction 1

Direction 2

7.3 Direction Analysis

Before making designs to a template to grow anything it was necessary to ask some users about their opinions about the bags. The next section is a discussion of this.

Introduction
A focus group was used to get feedback on the to directions. It was a necessary step to get insights on the perceived pragmatic quality, the experiential quality and the attractiveness of the bags.

Participants
Three Participants from the Industrial Design faculty of Delft University of Technology participated. Their respective disciplines were: Integrated Product Design, Strategic Product Design, and Design for Interaction.

Method
Participants were given the bags and asked to investigate the bag before. A sample of the material concept was provided, along with a picture of the pattern that is desired to use on the bag design. This was decided in order to get a holistic impression of the experience. After the participants finished, a short discussion continued with the vision presented.

Main Takeaways

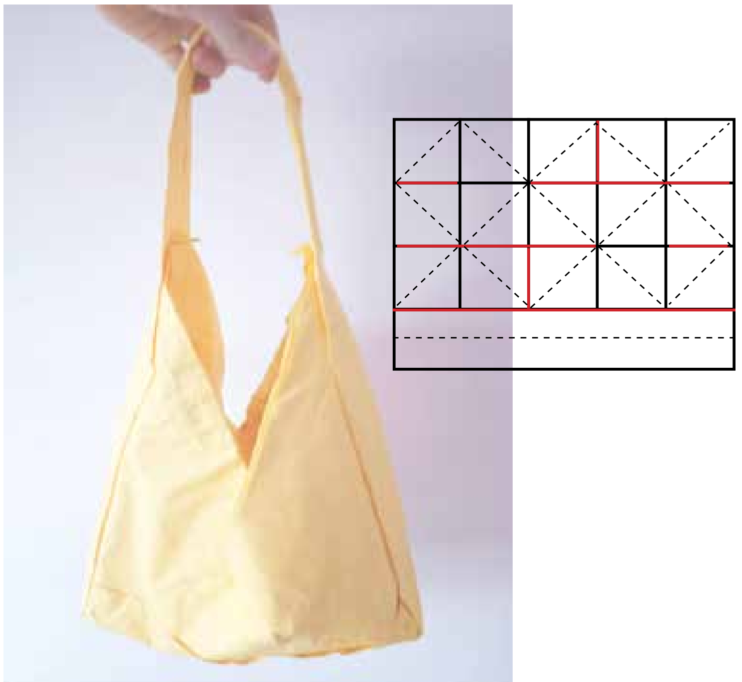
Typicality:
The material would be unique enough that the bag does not need to be a complex form and a more typical bag would be a better fit to balance the novelty of the material itself. For examples a tote bag was mentioned to be a typical form because of its current trend in fashion. The sack was preferred in this sense as it was closest to the tote but was also considered to be too feminine.

Past Inspiration:
The material evokes naturalness and nostalgic memories, some participants considered looking at old bags from the past to embody the form, to elicit a time when we were closer to nature.

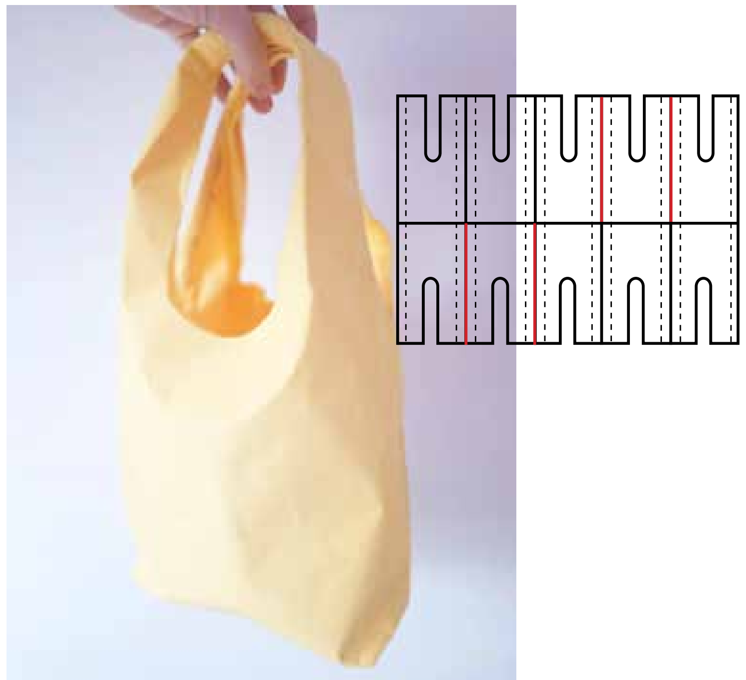
Vulnerability:
The origami bag was considered to be more handcraft with signs of making but the openness was considered impractical and vulnerable.

Figure 84: Small focus group

Direction 1



Direction 2



7.4 Experience Patterns

The MDD method suggests in the 3rd step to discover formal qualities that reflect the design vision. The formal qualities are explored further in this section, where patterns that are prevalent in society are extracted and applied to the design.

Introduction
In order to decide on the formal qualities of the bag and provide feedback for further development of the material, the question to be answered now are what are the interrelationships between the created materials experience vision and the formal qualities of materials and products? (Karana et al, 2015). That is, how can materials experience patterns be manifested? (Giaccardi & Karana, 2015; Karana, 2009). One meaning was firstly identified as important from the created vision to be further explored.

The vision statement I want people to trust the interwoven 'bio-composite' by designing a bag to represent its strength and exhibit the delicate root architecture through artisanal craft, bonding the wearer to a deeply evocative connection to nature."

Evocative is to call out or summon strong images, memories and feelings. From the experiential analysis it was seen this was often towards the past. Thus the meaning *'nostalgia'* is extracted.

Examples from daily life, existing products, and existing materials was collected into a collage, analysed and principles extracted.

The collage is presented to the right.

Figure 85: Collage

Main Takeaways
Based on the collage, some ideas, and design principles are discussed and concluded as follows:

1. Frugal Intelligence:
In the past careful management of material resources and using only what is necessary was prevalent. This translates to Interwoven through the ability to grow into the final form and leave no waste.

2. Patch work Patterns:
Handcraft signals showing signs of wear, using old carpets and sewing sections together into a new carpet that looks evocative of the past.

6. Traditional crafting:
Straw and rattan bundles which are highly flexible strands, natural in colour, were and are still braided into a frames to make baskets. This is a traditional craft, universe around the world and produces forms that can be utilised for Interwoven.

7.5 Concepts

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

1

Tote Bag

With this concept, a tote bag was specifically chosen because of the typical shape and due to its popularity in current culture. It allows for instant recognition as a way to facilitate the acceptance of the novel material in society. It hangs close to the body to stimulate a tactile connection to the roots and the feeling of nature. To bridge the aesthetic of craftsmanship with natures. It was decided to use a patch work of patterns to elicit evocative memories, and traditional images of the past. Finally, inspired by the burlap sack prints, a print here was placed to reflect the place of origin and the biographical identity of the seeds used to create the material.

2

Basket

With this concept, a basket form was used because it was noticed in the experience pattern vision that baskets are traditionally weaved out of straw and are universally recognised. Here the traditional craft of weaving is bridged with the craft of nature. The pattern structure is simpler than the previous concept because the form is more reminiscent of the past. Yet the exposed patterns share the story of the growth of the roots, and create an imperfect aesthetic that would act as active stimulation for cognitive and affective interactions. Again the stamp is used to reflect the place of origin and the biographical identity of the seeds.

Final Choice

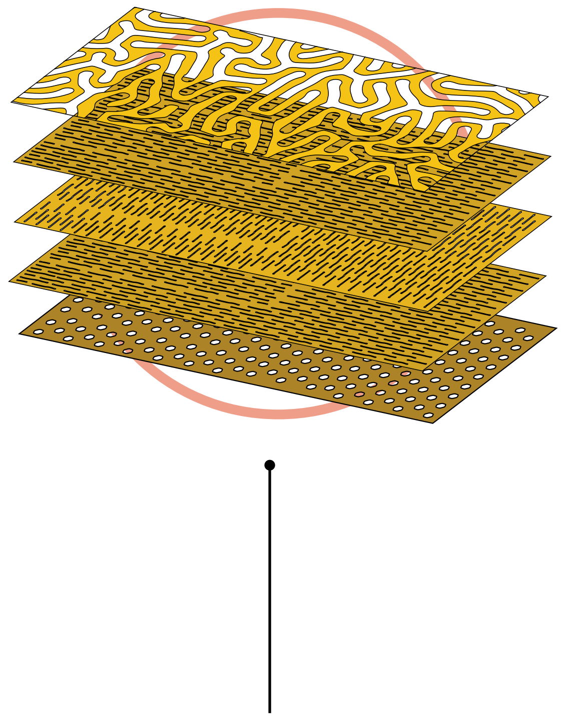
Based on the focus group insights, experience vision patterns and feasibility, the choice is made to select the tote bag concept, because it would facilitate greater acceptance, as it is already a loved bag in current culture. As well as being a simpler design to execute. Although it is considered less evocative of a connection to nature it is concluded that the material its self with a symbolic pattern is substantial enough.

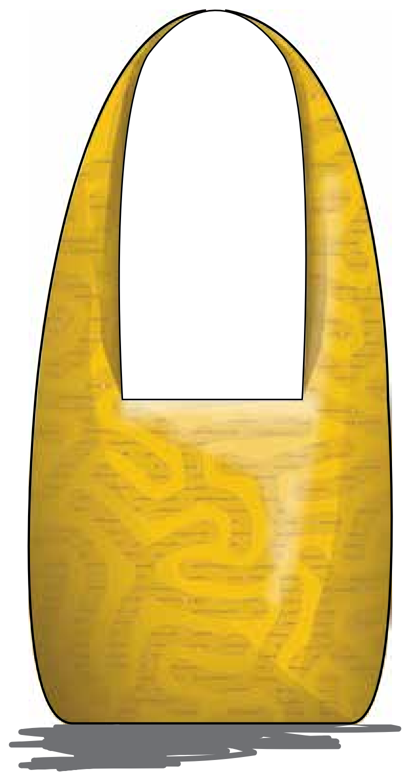
Features	Tote Bag	Basket
Simplicity	++	+
Evocative	+	++
Emotional Bonding	++	+
Nostalgic	+	++
Durability	++	+
Acceptance	++	+
Total	10	8

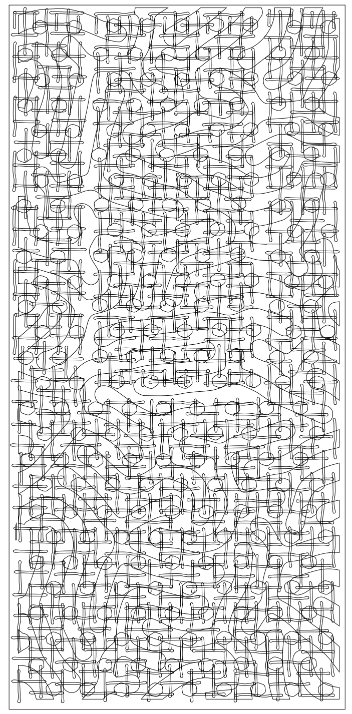
Figure 86: Datum to assess concepts.

7.5 Final Design

The final design is presented.





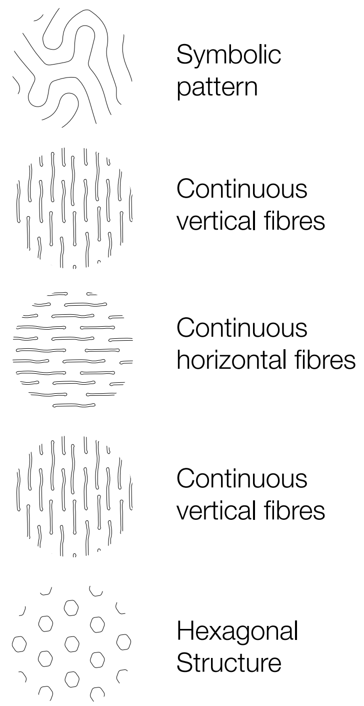


The final design takes into consideration the fibre orientation based on where the applied forces would be coming from when carrying a bag with objects inside.

For this reason the composite structure has two continuous linear pattern structures either side a continuous horizontal pattern. The linear pattern is designed so that there is as much interconnectedness between the roots to maximise root hair connection and the density. Additionally it would make it easier to harvest after growing as its a more stable structure.

The hexagon structure is used because of isotropic stability, as well as the perception to be durable of a regular pattern. The top layer is a reaction diffusion pattern of a labyrinth pattern type because it is used to symbolically represent the connection to nature. The pattern has a wide cross-section to create a greater contrast from the layers below.

The following pages show an illustration of how the bag would be made, and final material demonstrator.



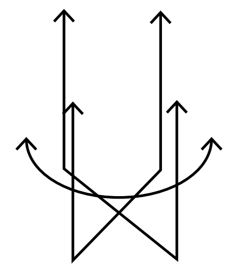
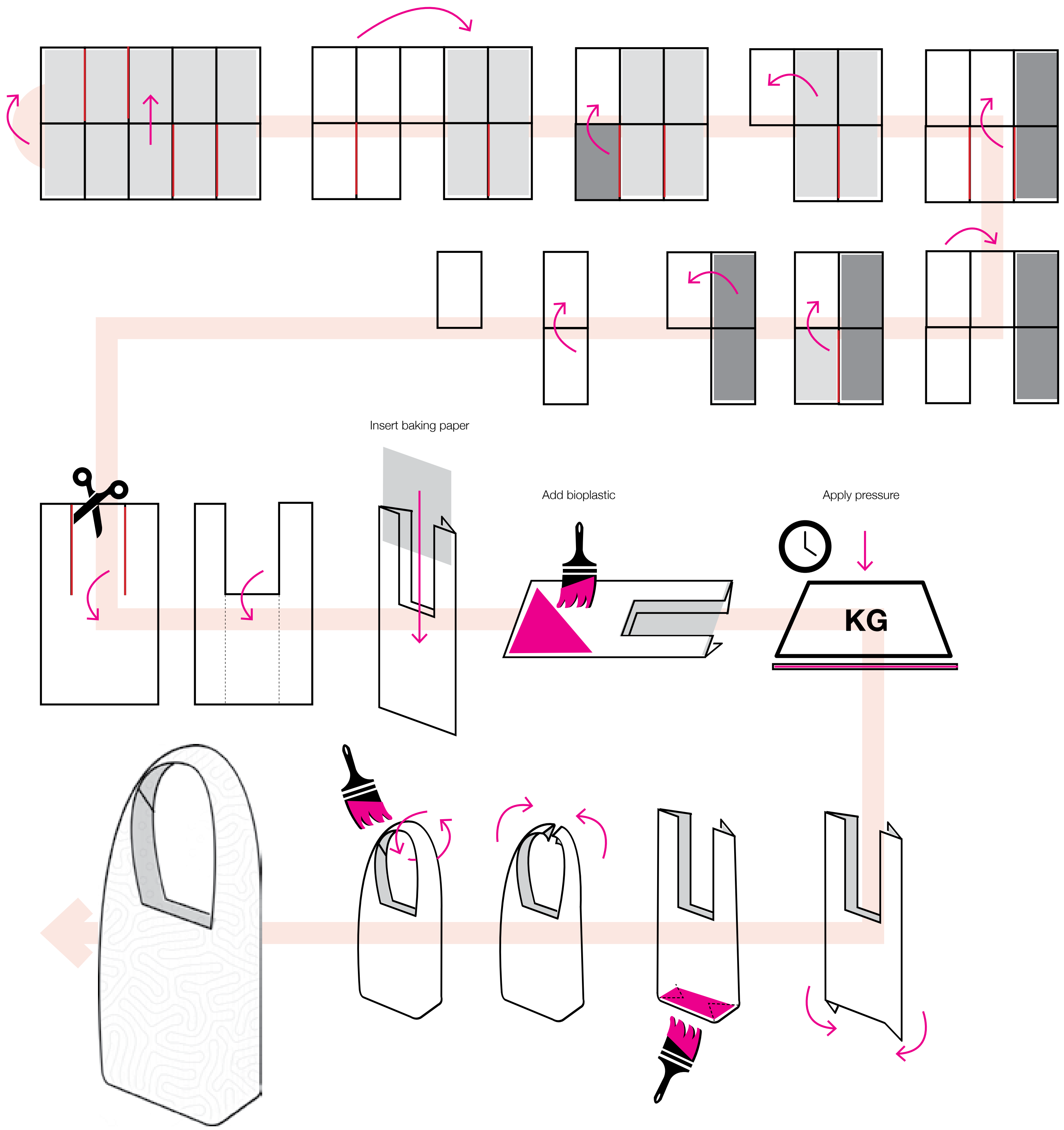


Figure 87: Illustration of the moments of force applied to the bag

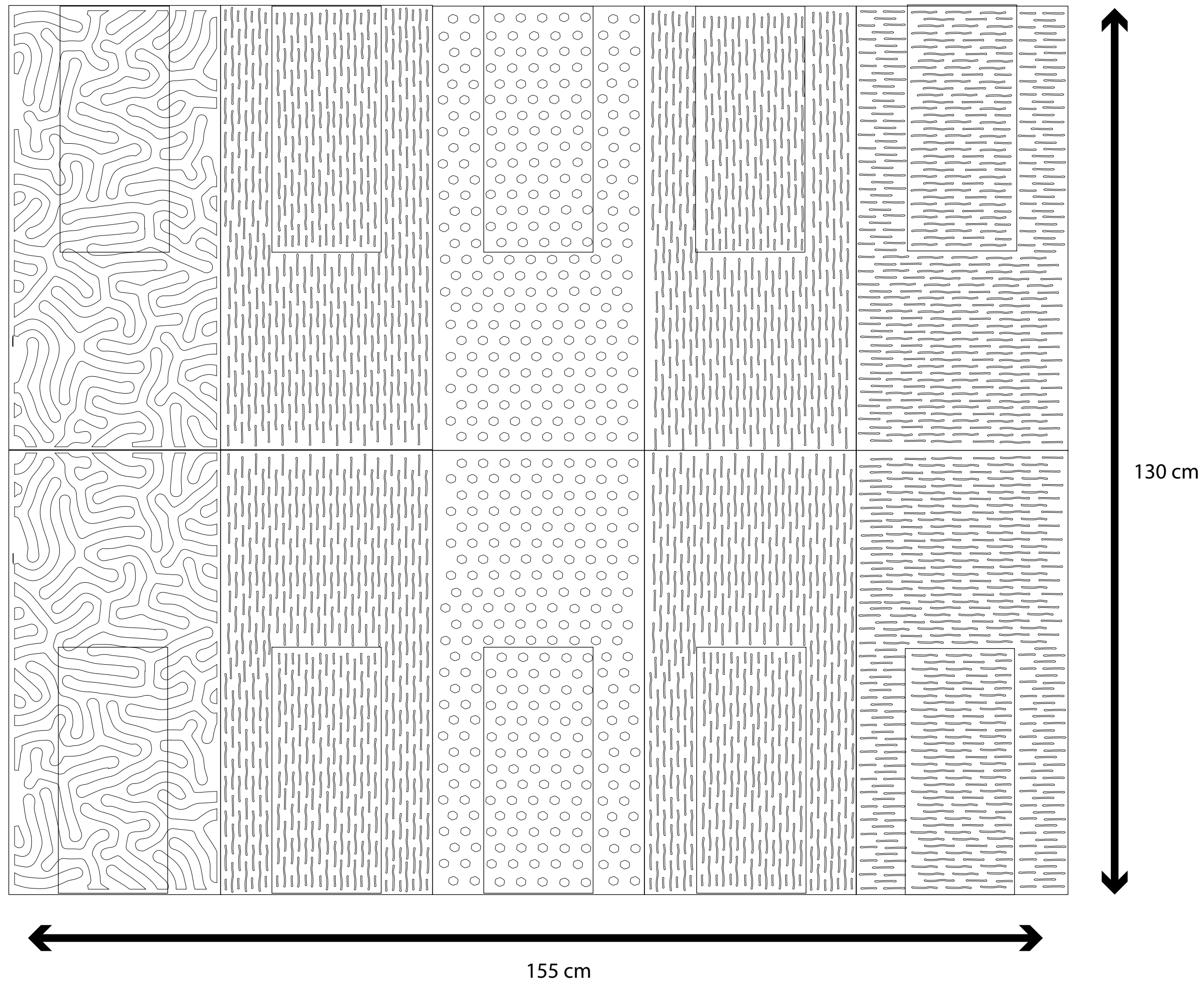
7.6 Flow Diagram

Below is a flow diagram of the making process from flat sheet of Interwoven after harvest to finished bag



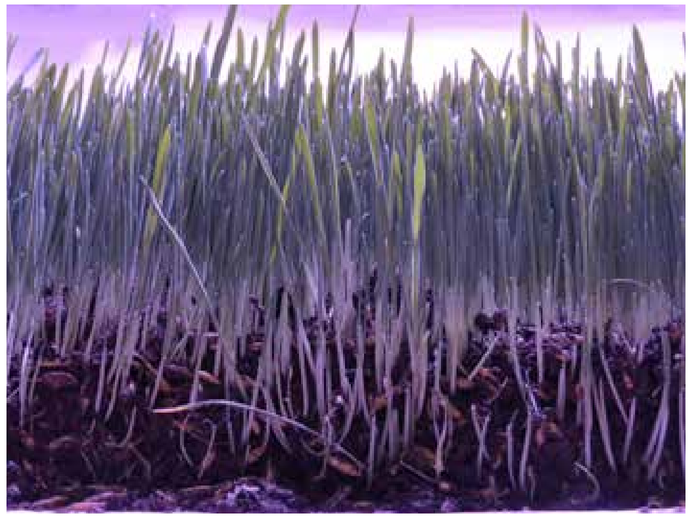
7.7 Final Pattern

Below is the final pattern layout to manipulate the roots.



7.8 **Final** Growth

Below is a picture of the final growth.



6.5 Kg of oat seeds
80L of pot soil
10 days growth

7.9 Conclusion

Unfortunately when working with an organism there is always a level of uncertainty in the final outcome.

The growth of the plants went very well and all seemed perfectly fine; however as mentioned there is always a level of uncertainty when collaborating with an organism. It is theorised that the roots reacted to a chemical and avoided the templates altogether. As disappointing as it might be that the final growth did not turn out the way it was hoped the remaining sheets were enough to make a material demonstrator with the samples in the order that the bio-composite is designed.

Final Reflection

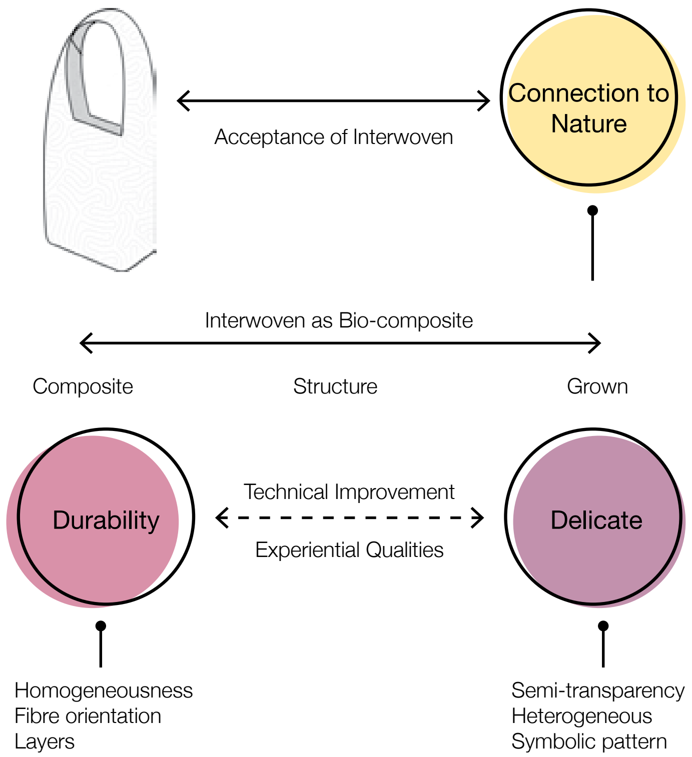
Interwoven: Bio-composite
The strength has been increased as a bio-composite structure with pectin as a matrix. Pectin bonds well with the roots, providing structural stability. Greater homogeneousness and density through a cross-sectional area increases the amount of root hairs and internal connectivity, providing more friction, contributing to the strength. Cultivation interventions were used, such as more seeds, plant vitamins, drought and greater soil depth to increase root anchoring, speed of growth and strength. Additionally, a wax surface treatment is used to make the composite water resistant. The advantage of growing is that the roots can be manipulated into the desired direction for specific fibre orientation required to resist force. The bulk of the work is done by the roots on their journey to find nutrients, creating its self beneath the soil. The all natural ingredients makes 'Interwoven: bio-composite' a natural material that comes from nature and can return to nature, standing as an example of cradle to cradle design that contributes to a less destructive textiles industry.

The root architecture creates an imperfect aesthetic qualities that has a natural look and feel which is perceived as durable. The visual and tactile ques are use to show reliability and reduce technical uncertainty. Additionally, fibre direction, visible layering and using patterns that contain regularity elicit durable perceptions. It became a balancing act to find how to express delicate qualities while still keeping the necessary durable properties. This was finally discovered between the layering to create a homogeneous effect that is coupled with a heterogeneous quality when viewed through light. This is an interesting balance of the two qualities required for perceptual delicacy and durability.

The most unique aspect of Interwoven is its origin. Exposing the root architecture reveals the traces of its growing behaviour, carrying the biography of the roots journey into the material. This creates an evocative connection to the material, which is significant for building a lasting relationship that can lead to emotional durability, and sustainable design.

Driven by aesthetic principles a pattern type superfluous with our connection to nature is symbolically utilised to create the meaning of connection and to make people think about future possibilities.

The ambition has been to create a textile that is both growing design and a bio-composite that can be trusted by people. Instead of creating a material that acts as a hypothetical what if, the decision was made to create a utility product in the form of a bag. This was to exhibit its strength as a bio-composite, and diffuse any worries about its technical ability as a surrogate material. As a way to lead to greater acceptance by the public and designers a like. A typical form was chosen to help manage expectations concerning utility and function to facilitate acceptance and connect craftsmanship of the designer to nature, being the main crafter.



The next page shows pictures of the final material demonstrator.

Recommendations

Technical tests
Further technical characterisation should be conducted to towards understanding Interwoven as a bio-composite. A more strategic approach is recommended, by altering the quantities of pectin, glycerol and water to characterise which ratios are optimal for value for strength.

Adding Colour
An interesting project lies in using natural processes to add colour to Interwoven. One such direction could be to utilise the oat grass and extract pigments to use in the textile itself. Another method is through adding colour dyes to the bioplastic.

Natural shading
Exploring Interwoven's ability to be grown into beautiful patterns that can be integrated into a window blind.

Circular process
It is necessary for the growing process, once harvested to be composted and become nutrients for the next batch of growing materials.

Self compositing
It would be interesting to investigate if the grass can be cut or pruned and then regrown into another template. This would reduce the amount of materials needed for each growth.

References

1. Antonelli, P. (2012). States of Design 11: Handmade Design. Domus n. 956. Retreived from: http://test.qrt.edidomus.net:4503/content/domusweb/en/design/2012/03/26/states-of-design-11-handmadedesign. html on February 2019

2. Ashby, M. F., & Johnson, K. (2013). Materials and design: the art and science of material selection in product design. Butterworth-Heinemann.

3. Ayala-Garcia, C., & Rognoli, V. (2017). The New Aesthetic of DIY-Materials. The Design Journal, 20(sup1), S375-S389.

4. Bahrudin. F. I and Aurisicchio (2018). The appraisals of sustainable materials.

5. Camere, S., & Karana, E. (2017). Growing materials for product design. In Proceedings of the International Conference of the DRS Special Interest Group on Experiential Knowledge and Emerging Materials (pp. 101-115).

6. Camere, S., & Karana, E. (2018). Fabricating materials from living organisms: An emerging design practice. Journal of Cleaner Production, 186, 570-584.

7. Characteristics of Monocotyledonous Roots | Botany. Retrieved from http://www.biologydiscussion.com/ root/characteristics-of-monocotyledonous-roots-botany/ 20692

8. Collet. C (2018) Bio-textile design practices for the bioeconomy and emerging organism industry.

9. Darwin, Charles; Darwin, Francisc (1881). The power of movement in plants. New York: D. Appleton and Company. Retrieved 24 April 2018.

10. Desmet, P. M., & Hekkert, P. (2007). Framework of product experience. International journal of design, 1(1), 57-66.

11. Dunne, A., & Raby, F. (2013). Speculative everything: design, fiction, and social dreaming. MIT press.

12. Ellen MacArthur Foundation, A new textiles economy: Redesigning fashion's future, (2017, http://www.ellenmacarthurfoundation.org/publications).

13. Front Page - Full Grown. (2019). Retrieved from https://fullgrown.co.uk/

F. Bahrudin and M. Aurisiahio (2017), sustainable materials in design.

14. Giaccardi, E., & Karana, E. (2015, April). Foundations of materials experience: An approach for HCI. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (pp. 2447-2456). ACM.

15. Geke Ludden, Sensory Incongruity and Surprise in Product Design (PhD diss., Delft University of Technology, 2008).

16. Grierson, C.; Schiefelbein, J. (2002). "Root Hairs". The Arabidopsis Book.

17. Guinée, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. The international journal of life cycle assessment, 7(5), 311-313.

18. Hathaway, R. L., & Penny, D. (1975). Root strength in some Populus and Salix clones. New Zealand Journal of Botany, 13(3), 333-344.

19. Hochholdinger, F., Yu, P., & Marcon, C. (2018). Genetic control of root system development in maize. Trends in plant science, 23(1), 79-88.

20. James Auger (2013): Speculative design: crafting the speculation, Digital Creativity, DOI:10.1080/146 26268.2013.767276

21. Jonathan Chapman, Emotionally Durable Design: Objects, Experiences and Empathy (London: Earthscan, 2005).

22. Karana, E. (2009). Meanings of materials.

23. Karana, E., Barati, B., Rognoli, V., Der Laan, V., & Zeeuw, A. (2015). Material driven design (MDD): A method to design for material experiences.

24. Elvin Karana, Owain Pedgley, Valentina Rognoli (2015) On materials Experience

25. Karana, E., Blauwhoff, D., Hultink, E., & Camere, S. (2018). When the material grows: A case study on designing (with) mycelium-based materials. International journal of design, 12(2), 119-136.

26. Karana, E., Pedgley, O., & Rognoli, V. (Eds.). (2013). Materials Experience: fundamentals of materials and design. Butterworth-Heinemann.

27. Elvin Karana, "Characterization of 'Natural' and 'High-Quality' Materials to Improve Perception of Bio-Plastics," Journal of Cleaner Production 37 (2012): 316–

28. Keeble, B. R. (1988). The Brundtland report:'Our common future'. Medicine and War, 4(1), 17-25.

29. Mackenzie, A. (2018). What Can You Use to Promote Root Growth?. Retrieved from https://homeguides. sfgate.com/can-use-promote-root-growth-75498. html

30. Mike Ashby, "Foreword: Materials Experience," in Materials Experience: Fundamentals of Materials and Design, ed. Elvin Karana, Owain Pedgley, and Valentina Rognoli (Oxford: Elsevier, 2014), xvii–xxii.

31. Mierzejewski, K. (2019). Information On How To Prune Roots On Houseplants. Retrieved from https://www. gardeningknowhow.com/houseplants/hpgen/pruneroots. htm

32. Monocotyledon. Retrieved from https://en.wikipedia. org/wiki/Monocotyledon

33. Osmont, K. S., Sibout, R., & Hardtke, C. S. (2007). Hidden branches: developments in root system architecture. Annu. Rev. Plant Biol., 58, 93-113.

34. Oxman, N., Ortiz, C., Gramazio, F., & Kohler, M. (2015). Material ecology.

35. Oxman. N., TED talk, Design at the intersection of biology and design. Retrieved from: https://www.ted.com/talks/neri_oxman_design_at_the_intersection_of_technology_and_biology

36. Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. The Design Journal, 20(sup1), S1167-S1184.

37. Phillips, K. (2017). Earth is on its way to the biggest mass extinction since the dinosaurs, scientists warn. Retrieved from https://www. washingtonpost.com/news/speaking-of-science/ wp/2017/07/12/earth-is-on-its-way-to-the-biggestmass- extinction-since-the-dinosaurs-scientistswarn/? noredirect=on&utm_term=.1f0c3b3a571d

38. Rognoli, V., & Karana, E. (2014). Toward a new materials aesthetic based on imperfection and graceful aging. In Materials Experience (pp. 145- 154). Butterworth-Heinemann.

39. Rognoli, V., Bianchini, M., Maffei, S., & Karana, E. (2015). DIY materials. Materials & Design, 86, 692-702.

40. Root Pruning and Benefits of Trimming Roots – GKVKs. (2018). Retrieved from http://www.gkvks.com/root-pruning-and-benefits-of-trimming-roots/

41. Roots | Boundless Biology. Retrieved from https://courses.lumenlearning.com/boundless-biology/chapter/roots/

42. Roots Station Lab. Retrieved from http://mrmitchellsbiology.weebly.com/roots-station-lab. html

43. Paul Hekkert and Elvin Karana, "Designing Material Experience," in Materials Experience: Fundamentals of Materials and Design, ed. Elvin Karana et al. (Oxford: Elsevier, 2014): 3–11.

44. Pieter Desmet and Paul Hekkert,s "Framework of Product Experience," International Journal of Design 1, no. 1 (2007): 57–66.

45. Rick Schifferstein and Lisa Wastiels, "Sensing Materials: Exploring the Building Blocks for Experiential Design," in Materials Experience: Fundamentals of Materials and Design, ed. Elvin Karana et al. (Oxford: Elsevier, 2014): 15–24.

46. Sauerwein, M., Karana, E., & Rognoli, V. (2017). Revived beauty: research into aesthetic appreciation of materials to valorise materials from waste. Sustainability, 9(4), 529.

47. Schoon, N., F. Seath and L. Jackson (2013). One Planet Living–The case for Sustainable Consumption and Production in the Post-2015 development agenda. BioRegional (www. bioregional. com).

48. Serenaa, C., & Elvina, K.. (2018) Experiential characterization of materials: Toward a toolkit. DRS

49. Simon. J., A. Pohlmeyer., P. Desmet (2015) Positive design reference guide, available at: https://issuu.com/delftinstituteofpositivedesign/docs/issuu

50. Smith, S., & De Smet, I. (2012). Root system architecture: insights from Arabidopsis and cereal crops. Philosophical Transactions Of The Royal Society B: Biological Sciences, 367(1595), 1441-1452. doi: 10.1098/rstb.2011.0234

51. Tanenbaum, J. G., Williams, A. M., Desjardins, A., & Tanenbaum, K. (2013, April). Democratizing technology: pleasure, utility and expressiveness in DIY and maker practice. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 2603-2612). ACM.

52. Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D. P., Fricker, M. D., ... & Nakagaki, T. (2010). Rules for biologically inspired adaptive network design. Science, 327(5964), 439-442.

53. Trewavas, A. (2003). Aspects of plant intelligence. Annals of botany, 92(1), 1-20.

54. Valentina, R., & Garcia, C. A. (2016). The material experiences as DIY-Materials: Self production of wool filled starch based composite (NeWool). MAKING FUTURES, 4, 1-9.

55. Valentina Rognoli and Elvin Karana, "Towards a New Materials Aesthetic Based on Imperfection and Graceful Ageing," in Materials Experience: Fundamentals of Materials and Design, ed. Elvin Karana et al. (Oxford: Elsevier, 2014): 145–53.

56. Van Bezooyen, A. (2014). Materials driven design. In Materials experience (pp. 277-286). Butterworth-Heinemann.

57. W.H. Freeman and Company. (2005). Biology of Plants, Seventh Edition.

58. William Myers, 2012, Book: Bio Design: Nature, Science, Creativity, Thames & Hudson Limited, 2012, p8.

59. Wu, J., Dick, C., & Westermann, R. (2015). A system for high-resolution topology optimization. IEEE transactions on visualization and computer graphics, 22(3), 1195-1208.

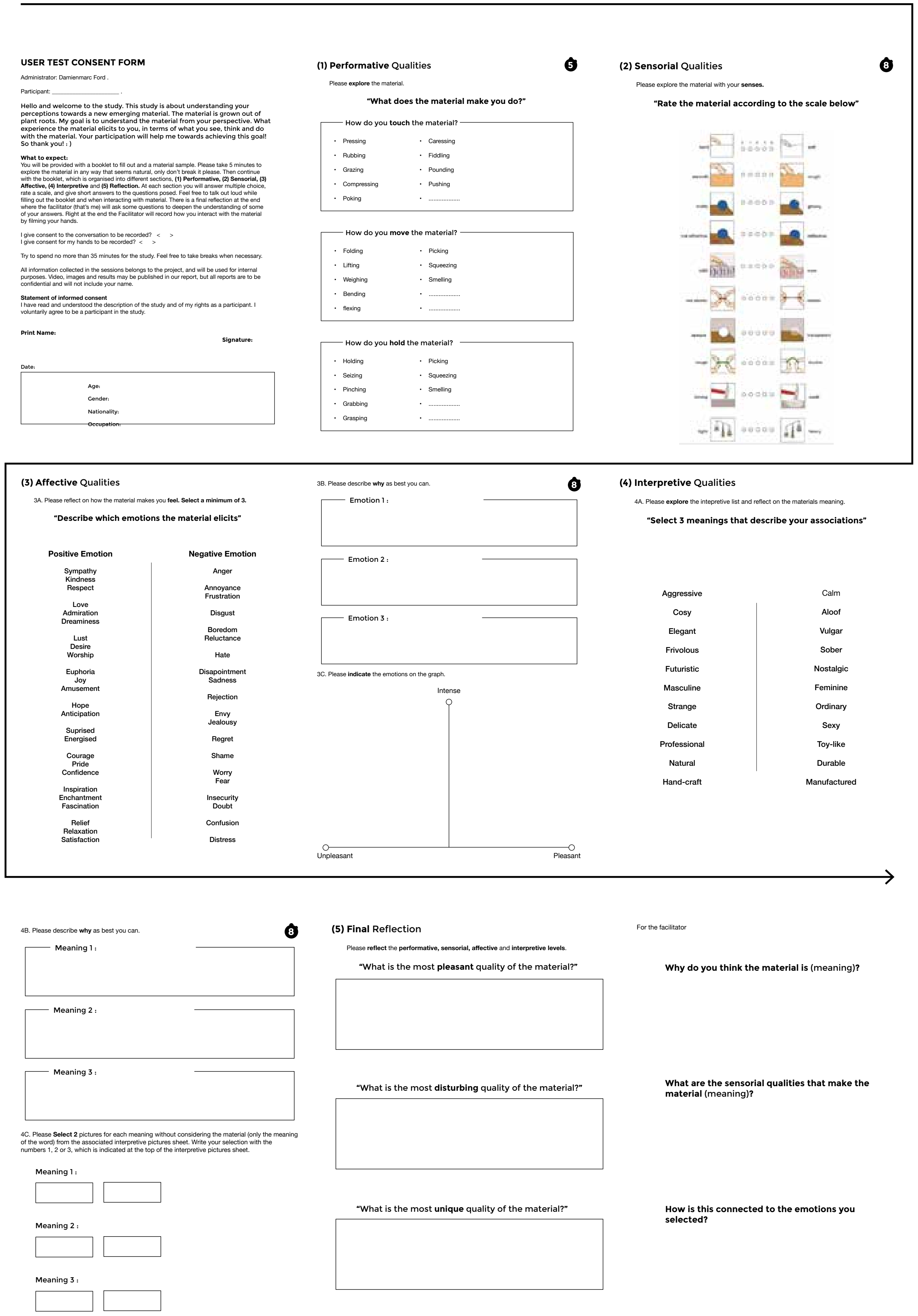
60. Zobel, R. W., & Waisel, Y. (2010). A plant root system architectural taxonomy: a framework for root nomenclature. Plant Biosystems, 144(2), 507-512.

Appendix A

Experiential Booklet
and interpretive
images

Appendix A

Booklet and images (next page) used for experiential characterisation



USER TEST CONSENT FORM

Administrator: Damienmarc Ford .

Participant: ______________________ .

Hello and welcome to the study. This study is about understanding your perceptions towards a new emerging material. The material is grown out of plant roots. My goal is to understand the material from your perspective. What experience the material elicits to you, in terms of what you see, think and do with the material. Your participation will help me towards achieving this goal! So thank you! :)

What to expect:
You will be provided with a booklet to fill out and a material sample. Please take 5 minutes to explore the material in any way that seems natural, only don't break it please. Then continue with the booklet, which is organised into different sections, **(1) Performative, (2) Sensorial, (3) Affective, (4) Interpretive** and **(5) Reflection.** At each section you will answer multiple choice, rate a scale, and give short answers to the questions posed. Feel free to talk out loud while filling out the booklet and when interacting with material. There is a final reflection at the end where the facilitator (that's me) will ask some questions to deepen the understanding of some of your answers. Right at the end the Facilitator will record how you interact with the material by filming your hands.

I give consent to the conversation to be recorded? <   >
I give consent for my hands to be recorded? <   >

Try to spend no more than 35 minutes for the study. Feel free to take breaks when necessary.

All information collected in the sessions belongs to the project, and will be used for internal purposes. Video, images and results may be published in our report, but all reports are to be confidential and will not include your name.

Statement of informed consent
I have read and understood the description of the study and of my rights as a participant. I voluntarily agree to be a participant in the study.

Print Name:

Signature:

Date:

Age:
Gender:
Nationality:
Occupation:

(1) Performative Qualities 5

Please **explore** the material.

"What does the material make you do?"

How do you **touch** the material?

- Pressing
- Rubbing
- Grazing
- Compressing
- Poking
- Caressing
- Fiddling
- Pounding
- Pushing
- ....

How do you **move** the material?

- Folding
- Lifting
- Weighing
- Bending
- flexing
- Picking
- Squeezing
- Smelling
- ....
- ....

How do you **hold** the material?

- Holding
- Seizing
- Pinching
- Grabbing
- Grasping
- Picking
- Squeezing
- Smelling
- ....
- ....

(2) Sensorial Qualities 8

Please explore the material with your **senses.**

"Rate the material according to the scale below"

(3) Affective Qualities

3A. Please reflect on how the material makes you **feel. Select a minimum of 3.**

"Describe which emotions the material elicits"

Positive Emotion	Negative Emotion
Sympathy Kindness Respect	Anger
Love Admiration Dreaminess	Annoyance Frustration
Lust Desire Worship	Disgust
Euphoria Joy Amusement	Boredom Reluctance
Hope Anticipation	Hate
Suprised Energised	Disapointment Sadness
Courage Pride Confidence	Rejection
Inspiration Enchantment Fascination	Envy Jealousy
Relief Relaxation Satisfaction	Regret
	Shame
	Worry Fear
	Insecurity Doubt
	Confusion
	Distress

3B. Please describe **why** as best you can. 8

Emotion 1 :

Emotion 2 :

Emotion 3 :

3C. Please **indicate** the emotions on the graph.

Intense

Unpleasant

Pleasant

(4) Interpretive Qualities

4A. Please **explore** the intepretive list and reflect on the materials meaning.

"Select 3 meanings that describe your associations"

Aggressive	Calm
Cosy	Aloof
Elegant	Vulgar
Frivolous	Sober
Futuristic	Nostalgic
Masculine	Feminine
Strange	Ordinary
Delicate	Sexy
Professional	Toy-like
Natural	Durable
Hand-craft	Manufactured

4B. Please describe **why** as best you can. 8

Meaning 1 :

Meaning 2 :

Meaning 3 :

4C. Please **Select 2** pictures for each meaning without considering the material (only the meaning of the word) from the associated interpretive pictures sheet. Write your selection with the numbers 1, 2 or 3, which is indicated at the top of the interpretive pictures sheet.

Meaning 1 :

Meaning 2 :

Meaning 3 :

(5) Final Reflection

Please **reflect** the **performative, sensorial, affective** and **interpretive levels**.

"What is the most **pleasant** quality of the material?"

"What is the most **disturbing** quality of the material?"

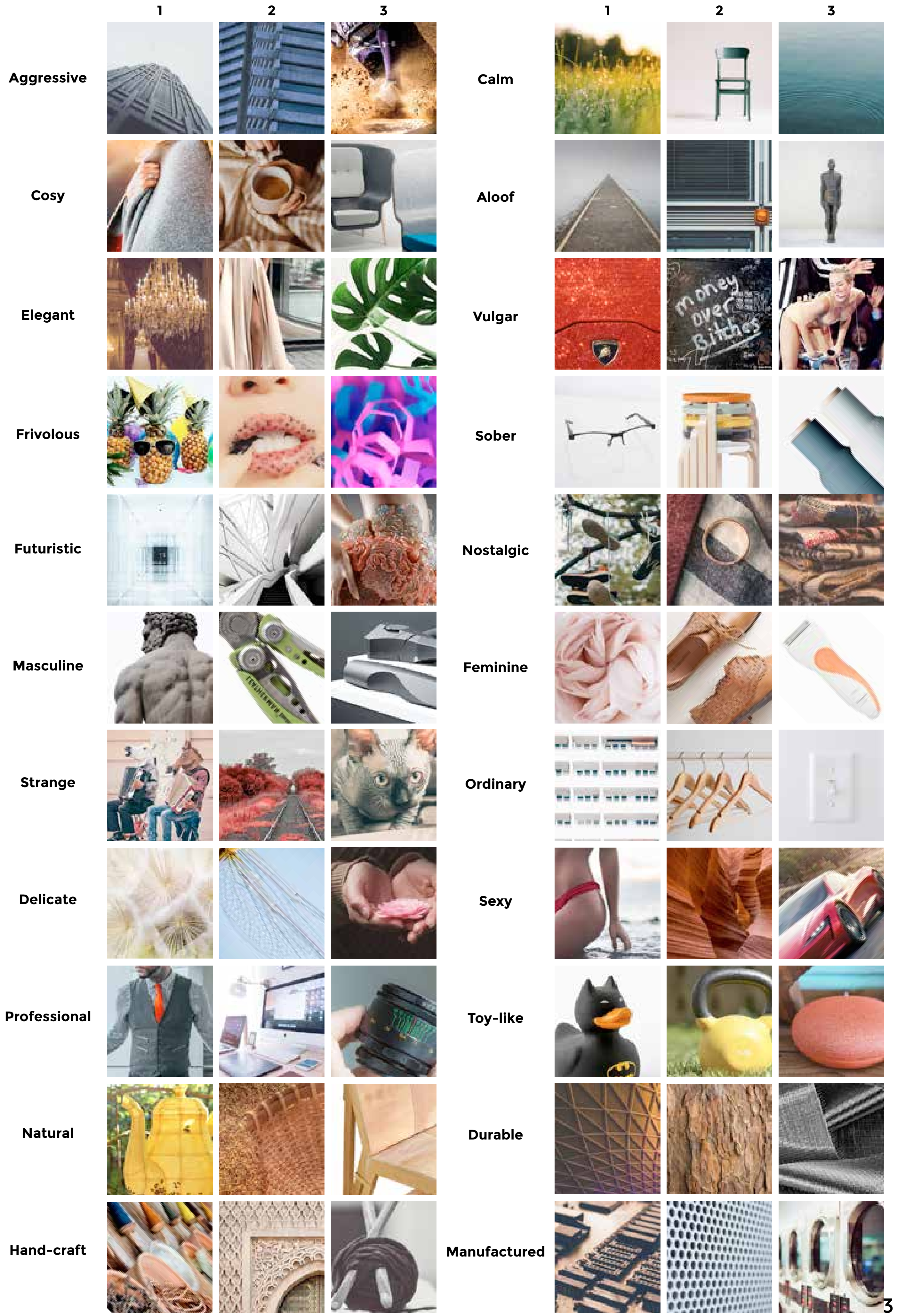
"What is the most **unique** quality of the material?"

For the facilitator

Why do you think the material is (meaning)**?**

What are the sensorial qualities that make the material (meaning)**?**

How is this connected to the emotions you selected?



Appendix B

Experiential and
technical analysis

Appendix C: Experiential results and analysis

Interwoven Original

Participants:

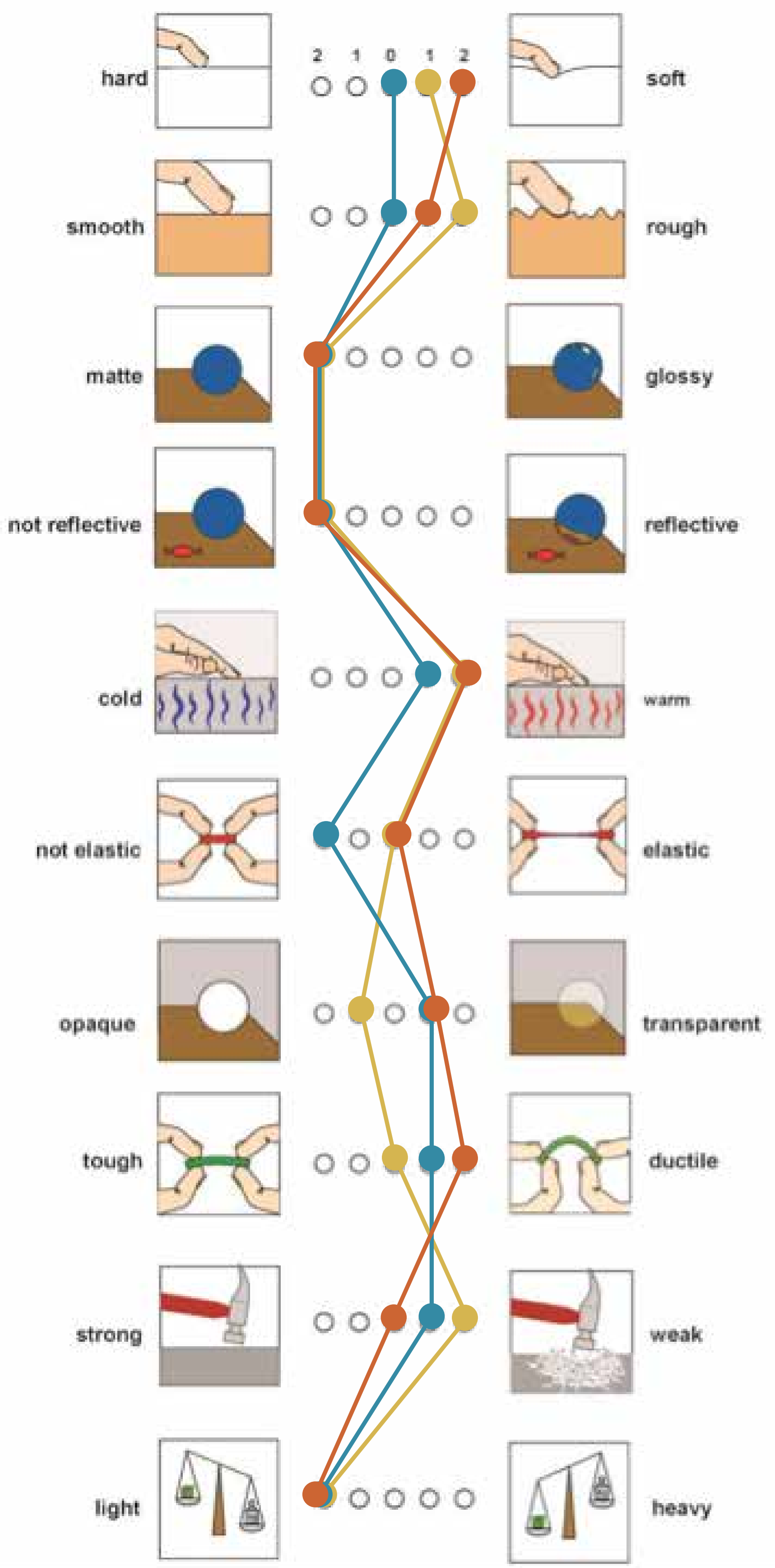
Age 23 - 26

Background: Design masters students

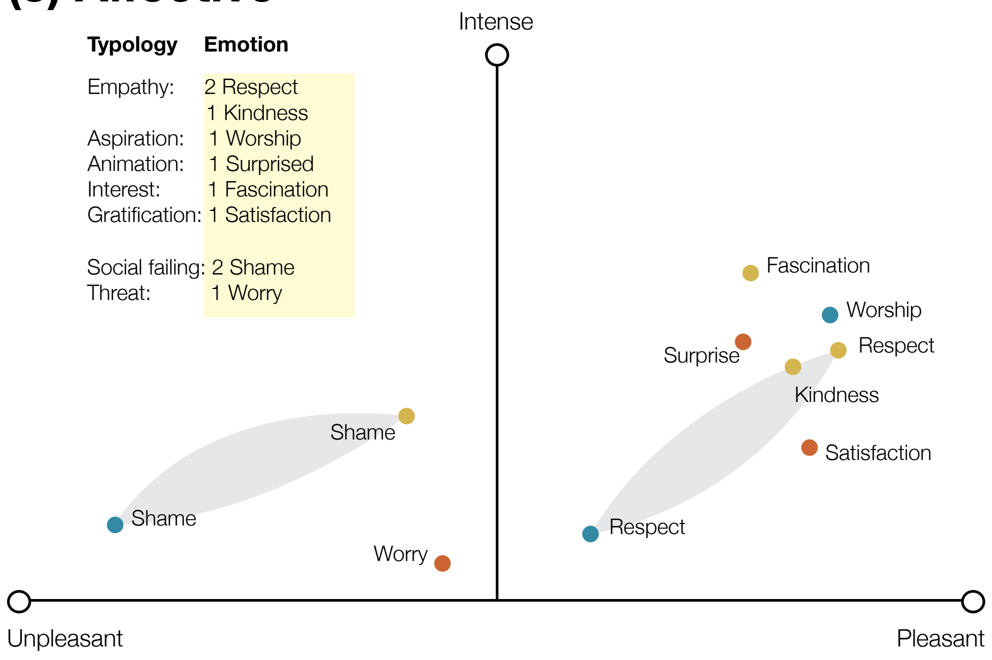
Italian, Spanish, Dutch

(1) Performative

(2) Sensorial

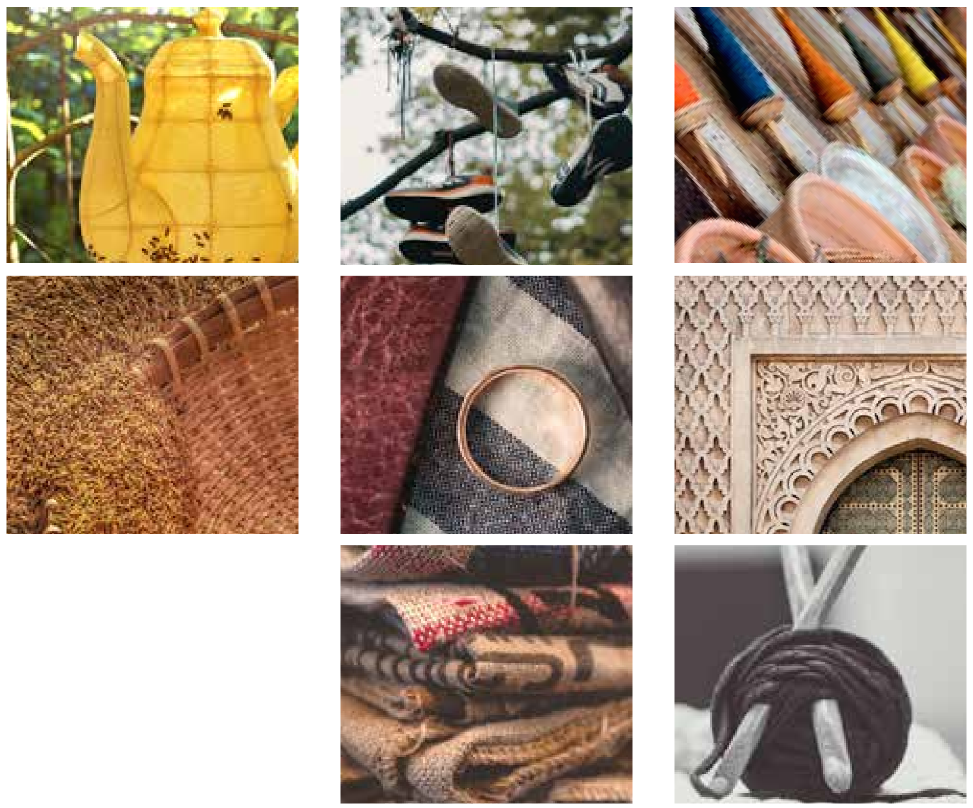


(3) Affective



(4) Interpretive

Natural n=2/3 **Nostalgic n=2/3** **Handcraft n=2/3**



Other meanings: Sober, delicate, feminine

Associations

"Reminds me of mother nature"

"Its like a burlap sack"

"I imagine it being a lamp shade"

"The pattern talks about the culture behind it, like Arabic mosques"

"Could be blinds"

"Close to God"

"Monk Material, like a worshipper, close to Earth"

"Foot binding children"

"Close to Earth"

Agar Bioplastic (B2)

Participants:

Age 25 - 29

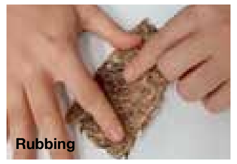
Background: Design masters students

Italian, Indian, USA / Dutch

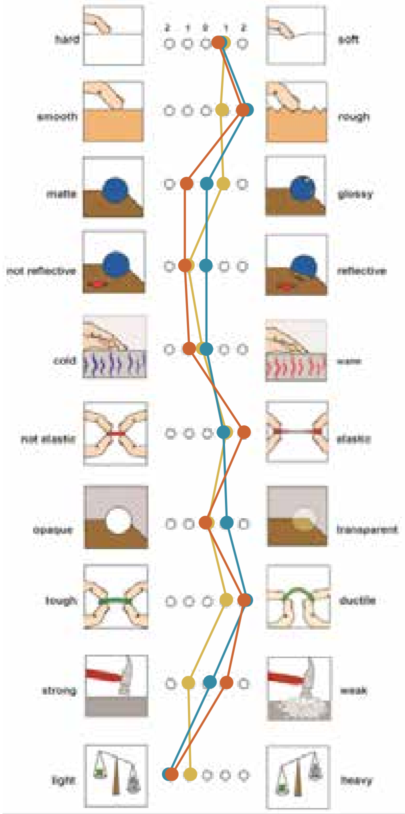
(1) Performative


Folding

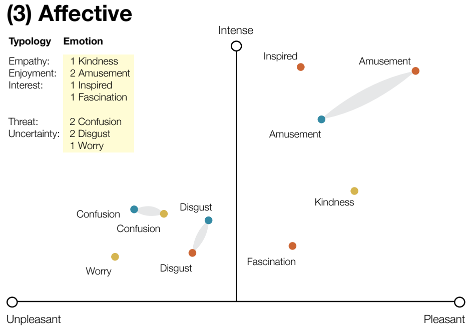

Stretching


Rubbing

(2) Sensorial



(3) Affective

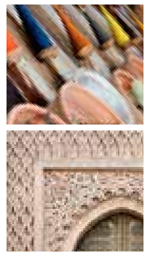


(4) Interpretive

Natural n=3/3

Nostalgic n=2/3

Handcraft n=3/3



Other meanings: Strange, Delicate

Associations

"Like a bracelet"

"When nature takes over"

Alginate Bioplastic (B4)

Participants:

Age 23 - 31

Background: Design masters students

Indian, Dutch, Mexican

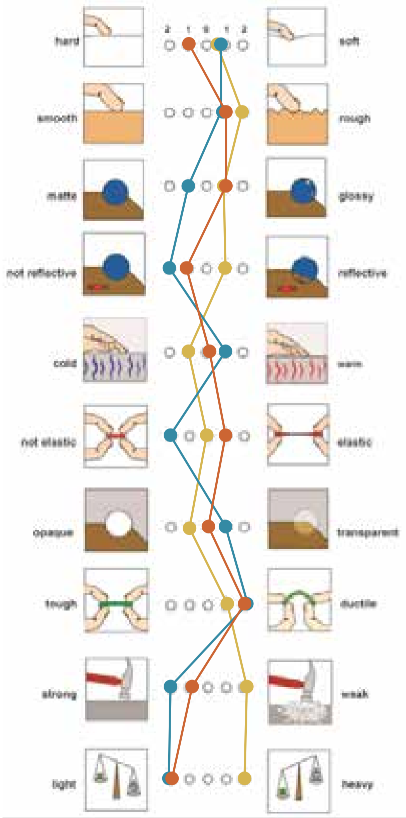
(1) Performative


Folding

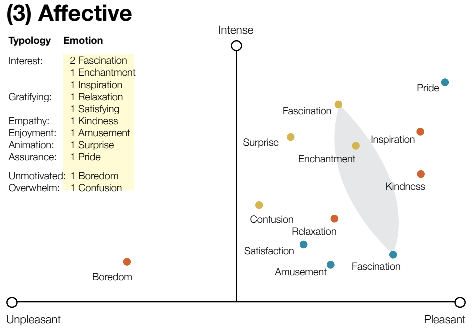

Stroking


Rubbing

(2) Sensorial

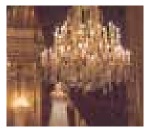


(3) Affective



(4) Interpretive

Elegant n=1/3



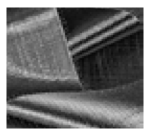
Nostalgic n=1/3

Delicate n=1/3

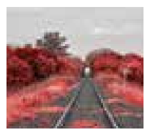
Aloof n=1/3

Natural n=1/3

Durable n=1/3



Strange n=1/3



Handcraft n=1/3

Sober n=1/3

Associations

"Like paper"

"Like a tent material"

"Plastic like"

"Like chaos"

"Like broom made of coconut tree spine"

"Could be a wall feature for a natural look"

"Reminds me of a cottage by the sea"

"Like a blanket"

"Reminds me of cardboard or cork"

"Compact composite"

Gelatine Bioplastic (B1)

Participants:

Age 23 - 26

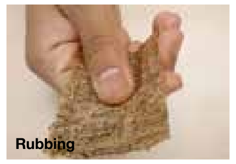
Background: Design masters students

Italian, Indian, Dutch

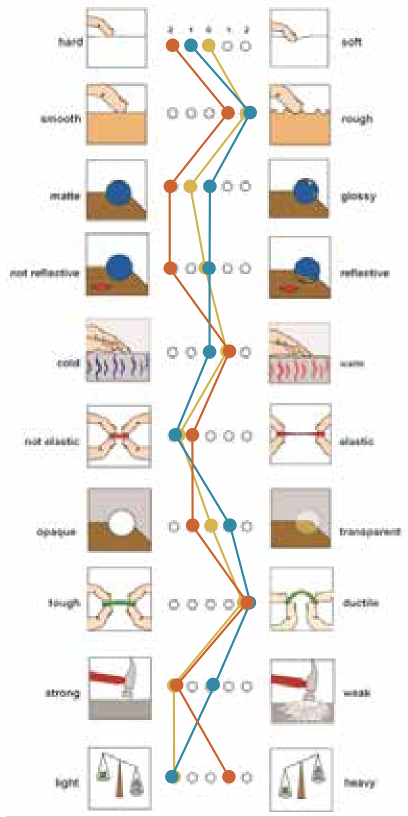
(1) Performative


Bending

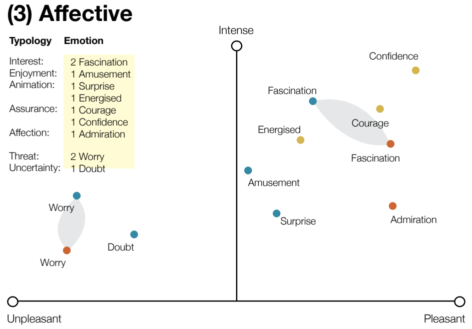

Folding


Rubbing

(2) Sensorial



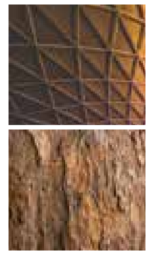
(3) Affective



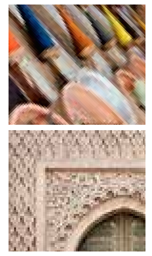
(4) Interpretive

Natural n=2/3

Durable n=2/3



Handcraft n=2/3



Other meanings: Nostalgic, Strange, Delicate

Associations

"Similar to a canopy"

"I see it as part of a backpack"

"Like a leather replacement"

"Reminds me of Indian jute bag"

" Watch band"

"Car seat cover"

"bag or chefs apron"

Pectin Bioplastic (B3)

Participants:

Age 25 - 29

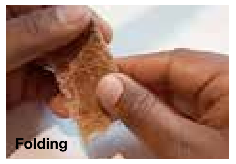
Background: Design masters students

Indian, Dutch, Dutch

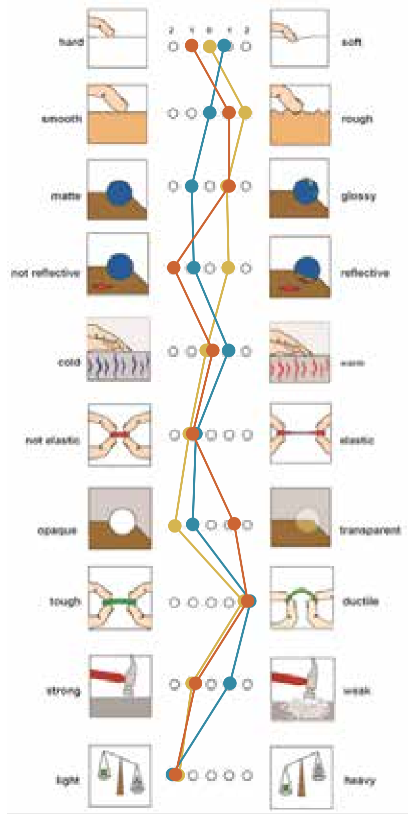
(1) Performative


Rubbing

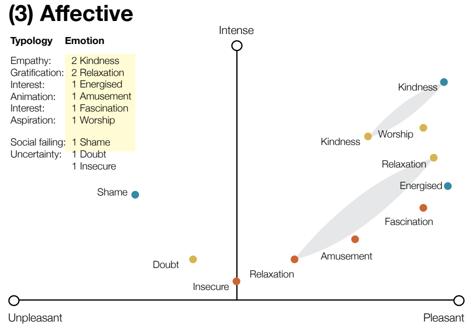

Bending


Folding

(2) Sensorial

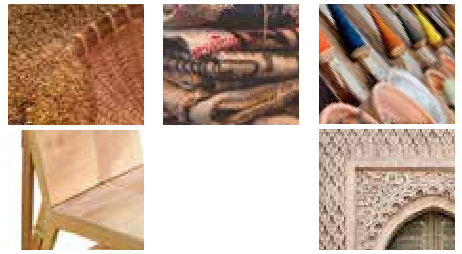


(3) Affective



(4) Interpretive

Natural n=2/3 Nostalgic n=2/3 Handcraft n=2/3



Other meanings: Ordinary, Delicate, Cosy/Calm, Frivolous, (Futuristic and Nostalgic at the same time)

Associations

"Like a carpet beater"

"Reminds me of the underside of a shoe"

"Like burnt skin"

"Like a table matt"

"I imagine it being under special food"

"Could be a suit"

"Could be a yoga matt"

"Reminds me of a temple in India"

"Like a jute fabric bag"

"Reminds me of my childhood"

"Something chaotic, reinforces natural causality"

Bioplastic analysis and discussion

Performative Level

The most common interactions are: Rubbing (11), folding (8), and bending (10). **The quality of rubbing was performed with delicate interest to feel the surface texture and explore the roots with fascination, followed by folding, which was done with stimulated affection like amusement after the first sensory exploration was complete. Finally, bending the material was a technical exploration to test the boundaries of the material but without damaging the materials because of uncertainty in the strength.**

Discussion
The rubbing is encouraged by the imperfect unique visual appearance of the roots, *"the more you look, the more you see"*, this is enhanced by the irregularity and *"untamed"* fibrousness, which has a tactile sensation of roughness. Although, some participants were surprised by the how some of the materials feel because of a perceived expectation being different to their perceptions, for example, alginate bioplastic *"looks organic but feels synthetic"* or similarly the pectin bioplastic *"looks rough but feels smoother".* This incongruity and unfamiliarity elicited an amusement with the material and stimulated folding in a playful way and sparked interest in its potential, *"I am curious about how I can take advantage of its properties",* with expressed association to natural products *"like a Jute fabric bag"* or natural materials *"like a leather replacement".* There was particular interest in its manufacturing *"I want to know the process behind it because you see the two materials"* This provoked the materials being held to the sky as participants assessed it, identifying some of the different layers. Once seeing its semi-transparency participants began to test mechanical boundaries, *"the roots direction suggest its elasticity",* delicately pulling in opposite directions. This created some doubt or insecurity in the technical ability of the materials strength "I'm afraid to brake it, so I'm careful", although it was mentioned that the glossiness of the gelatine and alginate *"makes it seem stronger"* than it actually is. To push boundaries further participants creased the pectin and alginate samples and were surprised to notice that *"they do not crease"*, creating satisfaction and repeat actions.

Sensorial Level

The materials are considered to be mostly **hard and soft, rough, matte but glossy, sort of reflective, neither warm nor cold, a little elastic, opaque but transparent, ductile, strong but weak, light, irregular and fibrous.**

Discussion
The fibrousness of the samples with its irregular heterogeneous quality has strong associations of being natural, which was emphasized by its rough feel and texture. On the other hand the glossiness of other samples like alginate bioplastic created association to materials far from natural, *"like a tent material",* and *"feels synthetic"*. Glossiness gives the impression of strength but unnaturalness, *"plastic like"*. The natural colour, roughness and combined ability to be ductile or bend / folded were associated to durable areas of products, *"I see it as the bottom part of a backpack"* and *" the underside of a shoe"* or durable materials, *" like a leather replacement"*. Additionally the perceived compactness of the material layers and greater homogeneousness of the irregular fibres was seen as strong and more trustworthy. Participants are less delicate in their interaction than in comparison to a sample that was more heterogeneous, more transparent and with small holes. The discrepancies between strong and weak are to do with the fibre direction, as participants knew that there would be greater strength in the fibre direction but not perpendicular to it. With nothing to compare to participants felt they were strong, but were not willing to add any more force, for fear of breaking the samples. Conversely, samples with root fibres that were flaky, or stringy or coming off the surface were seen as less complete and as a result more delicate and handcrafted. Discrepancies between hard and soft were from the ability of one material to be crumpled and return to its former position and being thin, whereas another sample being compact and unable to be dented. The discrepancy with elastic and not elastic is because the agar sample (B3) had high concentrations of glycerol in it which made it more elastic than the other bioplstics.

Interpretive Level

Interpretations evoked by the samples are appraised to the look and feel, material origin, associations, pragmatic utility and production of the samples, **natural (8), handcraft (8), nostalgic (5), strange (3), delicate (4), durable (3),** with additional interpretations of **sober, aloof, elegant, calm and frivolous.**

Discussion
Natural interpretations are to do with systemic appraisals of the materials origin or biography and knowing the materials were *"made by nature"* and its life-cycle as *"something that goes back to nature"*, in reference to its biodegradability. Additionally the non-regular, non-uniformity and heterogeneous effect of the roots being everywhere, and *"untamed like nature"* elicited connection, *"roots for me make me feel connected"* with further existential associations relating to existence that *"reinforces natural causality",* and positive cathartic emotions like kindness, *"returning to something that was you all along".* Similarly **nostalgic** interpretations were to do with the personal past, *"reminds me of my childhood"* and our collective existential past with nature, as the roots reminded users of their *"symbiotic relationship with nature",* and association to products in places that are to do with the worship of existence, *"reminds me of a jute carpet in temples in India".* The heterogeneous *"natural look and feel"* created **handcraft** interpretations that are in reference to the manufacturing of the samples as participants saw *"signs of making",* noticing there is some kind of resin that keeps the roots together and patterns that are not natural. In addition the heterogeneous root architecture was interpretative as **delicate**, particularly if the sample was thin, had a gold colour, "the roots are together and you can see and touch the fibres". Whereas **durable** interpretations came from rough texture, natural colour finishes, clean cut edges, ductile and bendy behaviour in the material and the ability for some of the samples to be creased and return to their original position. Finally **strange** interpretations came about from participants experiencing contradiction to their senses, where the natural, fibrous look was contradicted with a plastic shine but a paper quality touch. Similarly, a visually rough looking root architecture contrast with a smoother tactile experience.

Affective Level

The emotions mentioned are visualised on the map. The positive emotions the samples trigger are; **fascination (6), amusement (4), kindness (4) relaxation (3) surprised (2), inspiration (2), energised (2)** with additional positive emotions such as, **enchantment, satisfying, pride, worship, courage, confidence and admiration.** The negative emotions triggered are, **confusion (3), worry (3), disgust (2) and doubt (2),** additionally **boredom and insecure.**

Discussion
The emotions evoked are in general mostly positive. **Fascination** is initiated with the visual aesthetics and sensorial aspects of the random root architecture as there is "a lot to explore". Predominately the appraisals are to do with inspired and energised curiosity of the potential 'use' of the material as participants wondered "what are the possible uses of this?". As designers they questioned what they could do with it themselves and how it was made, identifying that it is "non-standard" and want to know about "analysing its technical aspects" because its unfamiliar to them and novel. The incongruity of the visual and tactile sensorial qualities elicited **surprise**. Participants found its ductility and texture "fun to play with", evoking **amusement** and enjoyed the technical ability of the material to return to its former position after being creased. **Relaxation** was elicited because of its natural colour and being associated to products to do with relaxing practices "like a yoga matt", which are often made of unnatural materials. Interestingly the participants would reflect on them selves and their values with these materials, considering its origin, identifying that it "requires nurturing" to create, and being "made by nature" elicited feelings of humility or pride, emphasised by its expressive "delicate looks", and lack of straight angles evoking **kindness** towards the material and recognising that showing its biography, "you don't hide it is made of roots" is a strong message about someone's values, provoking existential association of connectedness "we are doing it all together". Conversely, all the **negative emotions** are to do with technical appraisal based on the prior knowledge of its origin and concerns with its strength "Afraid I'm going to break it" and its semi-transparency provoked uncertainty in its use in time, "doubtful it will last a long time".

Affective Pattern:
Novel and unfamiliar sensorial qualities spark fascination, incongruity of the senses elicits surprise and exploration of its performance eliciting amusement at its pragmatic ability, evoking further interest in its potential uses, but raises concerns about it technical limitations and creates uncertainty due to knowledge of its origin. Conversely the sensorial biography elicits kindness towards the material through self reflection towards one's values and outward self perceptions, as well as deeper inward perceptions to our connectedness to nature.

Final Reflections

In the final reflection participants considered the most pleasant quality of the materials to be its natural look and feel. The natural colour, randomness of the fibres and the roughness of the materials invites touching and creates a tactile connection to nature, with a "one on one connection to nature", some participants mentioned that the incongruity of their senses, enhanced this appreciation, particularly when it looks rough and natural but felt smoother than expected, like with pectin bioplastic (B3).

The most unique quality was considered to be the origin of the material that was made apparent by the roots architecture and visible behaviour, and prior knowledge of its biography. The interwoven roots are "raw and untamed" and uncontrollable in its creation, creating an imperfect quality that is aesthetically pleasing to look at. Every aspect of the samples are different from its self, making each piece individual and "super customised by nature", therefore each sample is novel. In addition, the heterogeneous aesthetic contained within a single form, coming together as one "like humanity" is symbolic of our connection to nature and each other.

To finish the most disturbing quality is to do with insecurity or disgust towards dirt or soil particulates being viewed as fungal growth, that would have an effect on their health. In addition, participants felt unsure about the materials technical strength because they knew the materials origin.

Textile and **Non-woven** results
- **Organic pattern (T1)** Vs **Geometric pattern (T2)**

Participants:

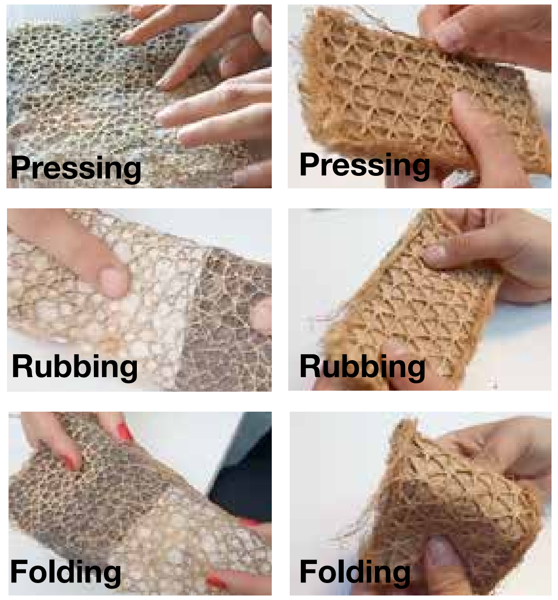
Age 22 - 27

Background: Design masters students from Industrial Design and Engineering at TU Delft

Belgium, Dutch, German, Italian n=6

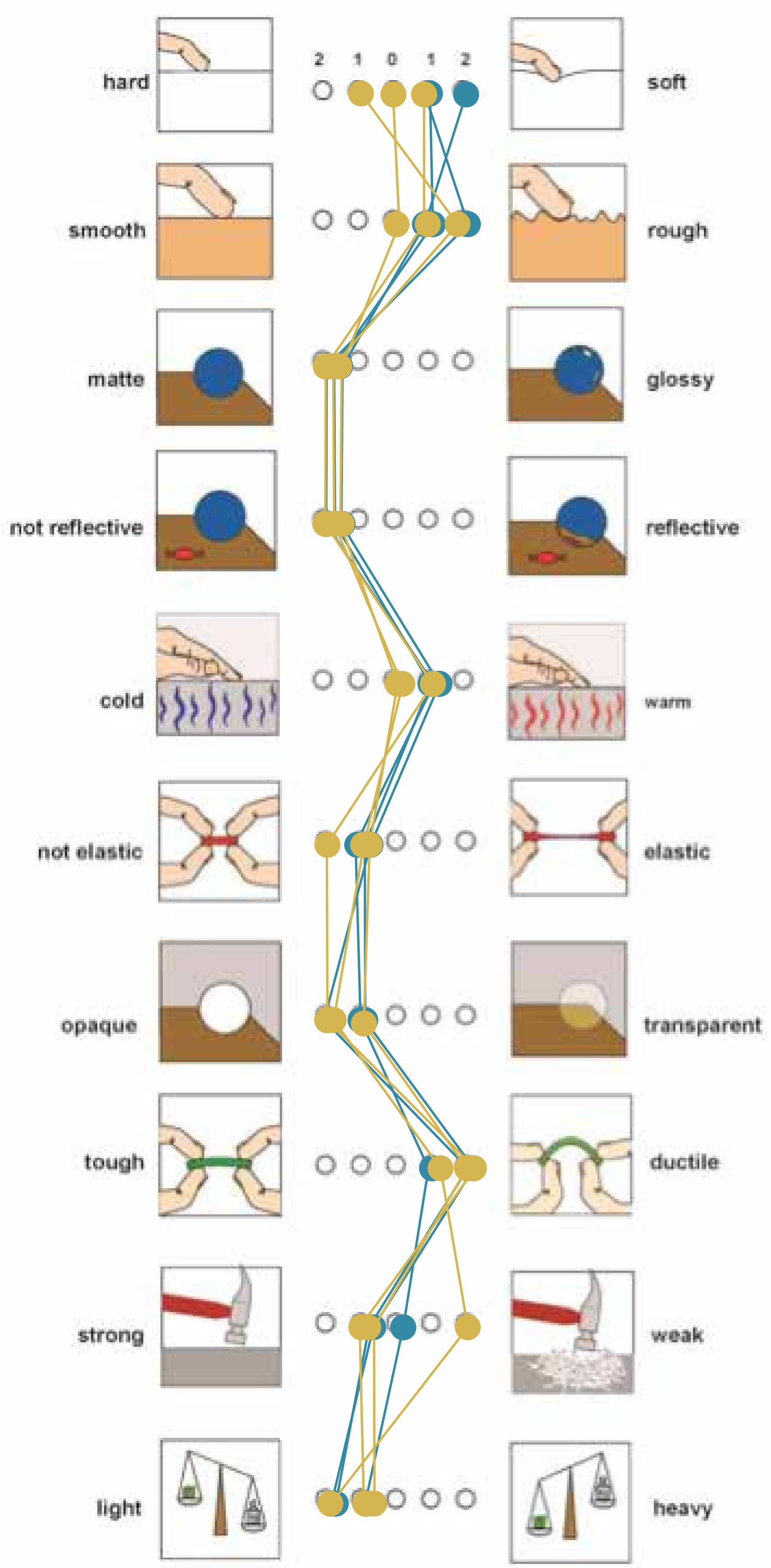
(1) Performative

T1 **T2**

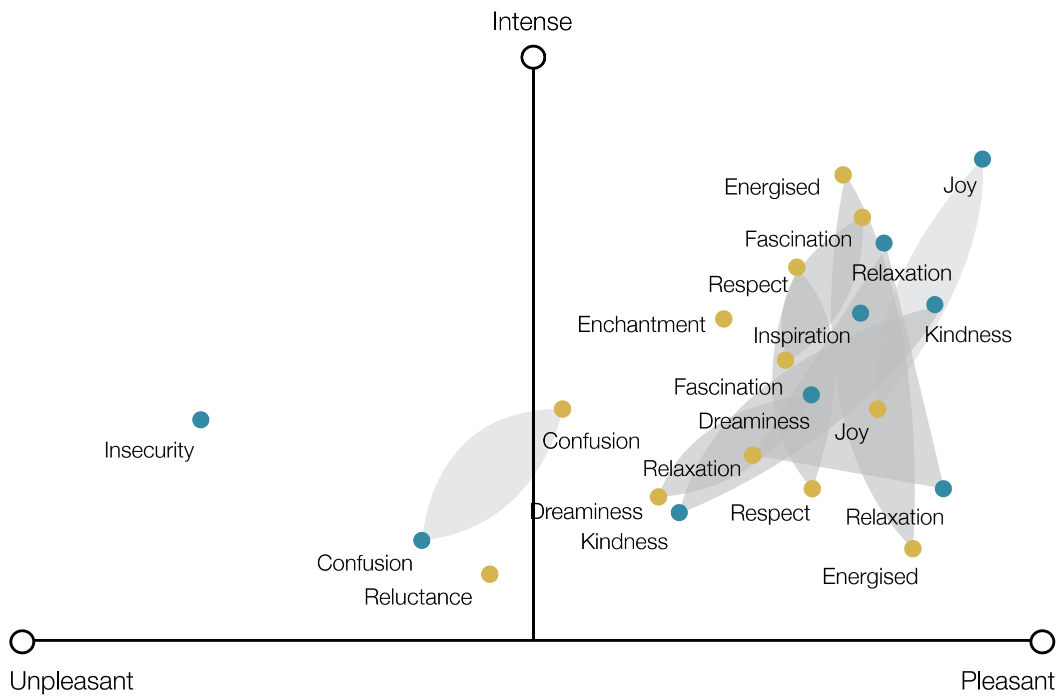


Pressing n= 6/6 - Sensory exploration
Rubbing n= 5/6 - Affective response
Folding n= 4/6 - Technical exploration

(2) Sensorial



(3) Affective



(4) Interpretive

Natural n=6/6

Cosy n=5/6

Futuristic n=3/6

Handcraft n=2/6

Nostalgic n=1/6

Sober n=1/6

Associations

"Packaging"

"Like hemp fibres"

"Could be a pillow"

"Could be the bottom of a shoe"

"Relaxing matt"

"Like sitting in front of a fire place"

"Terraced farming"

"Like a cloud"

"Tribe like environment"

"Similar to hobbit, trolls and stuff"

"Super nice bathroom floor"

"Reminds me of oat meal fields"

"Like a fuzzy beard"

"Memories of walking in nature"

"Roots take me back to a world I never lived in"

"Really good to be pretending to be something its not"

Results and Analysis

Textile and non-woven samples are analysed and discussed here.

Performative Level

The most common interactions are pressing (5), rubbing (3) and folding (4). **The quality of pressing was done delicately at first to explore the sensory stimulation of the raised roots and feel through rubbing the tactile roughness of the roots in contrast to its lower material. As understanding of the materials grew participants began to use them with more confidence by bending or folding to test its practical boundaries, although this was also done with carefulness.**

Discussion
The pressing was initiated with the sensorial visual contrast between the roots and textile or the visible depth between the roots and the underlying material because participants were trying to understand the difference between the top and bottom materials. Bending and folding were technical explorations to test the materials practical performance. The non-woven material was considered more durable because the pattern is a constant tessellation of triangles, a strong structure from engineering, as well as being thicker than the other textile sample.

Interpretive Level

Interpretations evoked by the samples are appraised to the look and feel, material origin, associations, use and technical ability, **natural (6), cosy (5), futuristic (3), handcraft (2),** with additional interpretations of **sober and nostalgic.**

Discussion
Natural interpretations are to do with the biography of the material because “its nature”, meaning its created by nature by the natural process of growth. This natural effect was appreciated with the regular organic pattern that “looks unrefined” as it fades from a more dense pattern to less dense. In addition its imperfect form elicited natural and sober interpretations because of rough edges and lose ends giving the sense “its still alive”, and that the decision was taken to show the roots and “not try to hide that its unfinished”. Similarly, the defined patterns that showed evidence of imperfection, meaning “not machine made” evoked handcrafted interpretations, which has a “kind of warmth” to it, evoking interpretations like cosy, due to its natural colour and softness. Interestingly both samples evoked futuristic interpretations because it “paints a picture of people living in harmony with nature in the future”, the systemic knowing that we as a species need to reconnect and “integrate natural materials into our future”.

Sensorial Level

The material is considered to be mostly **soft, rough, matte, not reflective, warm, not elastic, opaque, ductile, strong but also weak, light, fibrous, regular.**

Discussion
Both materials were considered soft, because of the ability to be compressed slightly. This is more apparent in the non-woven material. The rough tactile qualities were stimulating for participants to rub and to explore. It was considered a nice contrast to have two qualities that you wouldn’t expect together, such as rough and soft or similarly, a regular geometric pattern that feels soft. Discrepancies in strong and weak are to do with the visual strength of the patterns, the regular organic pattern of the roots on the textile was considered to add strength to the textile, this is the same with the regular triangle pattern of the non-woven because collectively together they are perceived as stronger but as individual strand, the participants knew that the origin of the material was considered weak.

Affective Level

The emotions mentioned are visualised on the maps. The material samples triggered positive emotions, such as, **relaxation (3), fascination (2), kindness (2), joy (2), dreaminess (2), respect (2), energised (2), enchantment (2) and inspiration.** While the negative emotions triggered are, **reluctance, confusion, and insecurity.**

Discussion
The emotions evoked are in general mostly positive. Relaxation was elicited because of the origin of the materials with consideration being given to natures rejuvenating quality as “nature is relaxing” and that its a new material which is inspiring. Interestingly, the origin of the material also elicited respect, because of “respect towards nature”, and that the roots look delicate and the perception that they will break easily so care must be given when interacting with the material, as a sign of respect. In the sense of how you show “care and respect to your elders”, which are our roots. Further emotions, such as energised, joy, and fascination are evoked specifically through the sensorial domain, by the look of the patterns and the touch of the roots. Both samples have different looks but rough tactility and visual signals of imperfection. The non-woven sample has a geometric pattern that is in contrast to its softness, while the textile sample with an organic pattern was associated to “trolls and stuff”, and more ‘dreamy’. All the negative emotions are to do with the concerns about the future use of the material, knowing that it is made of roots, “will it last long?”.

Final Reflections

In the final reflection participants considered expressive semantics the most pleasant quality, such as the “warm and earthy feel”, which is created with the natural colour, rough tactility and imperfect sensorial qualities that create a natural and dreamy interpretation, “taking me to a world I’ve never lived in”, which is enhanced with the olfactory of the roots. Secondly, the most unique quality is to do with the life cycle of the material and its origin, because its a resource, which is not depletable, meaning its renewable and that CO_2 is removed out of the air in its creation. In addition you get to “touch something you wouldn’t normally”.

To finish the most disturbing quality is the dirt and residue that falls off the material samples and is left on the fingers.

Main Takeaways

Sensorial

1. Regular durability
Individual strands of fibre are considered weak but the regularity of a pattern elicited the perception of durability.

2. Stimulate exploration
Participants rubbed to explore and to understand the changes in the depth of texture.

Performative

3. Delicate behaviour
The roots architecture look delicate and evoke careful interactions and behaviour.

Affective

4. Respect to nature
The origin of the material plays a strong role in positive emotional appraisals and associations of connection to nature.

Interpretive

5. Hopeful future
Root architecture evokes natural interpretations and associations of living in harmony with nature in the future.

6. Imperfection is naturally cosy
Imperfect aesthetic in the material, through rough tactility, natural colour, and imperfections evokes natural and cosy interpretations.

7. Unique Origin
The life cycle of the material is positively appraised as sustainable when considered from a systemic perspective. I.e. cleans CO_2 and is a renewable resource.

Experience as Material Potential

Experience Framework

Through the lens of the Materials Experience Framework, tinkering with interwoven was conducted at an early stage of the process. Through active participation and being an active maker of the material (Myers and Antonelli, 2012; Rognoli et al., 2015), the DIY approach (Rognoli et al., 2015) opened up the possibility to discover novel potential. Imbued with experiences the material Interwoven and developed samples were experientially characterised (Karana et al., 2015) in terms their sensorial, affective, interpretive and performative qualities. This has helped identity how the materials are experienced by people and has identified the patterns of material experience (Giaccardi and Karana, 2015). For this project it is seen that experience is the main material potential.

In this section, material potentials are described based on the tinkering and the technical and experiential characterisation of the material samples. The type of potentials are based on the framework created by Barati (2019), and include other potentials to experience, such as form, function and affordance.

Form and Function

The roots bond well with different bioplastics while still retaining the visual aesthetic of the root architecture. Combing Interwoven with bioplastics into a bio-composite increases the strength. A key part of the brief to make Interwoven perform as an applicable textile while still retaining its delicate look. Intermediate technical characterisation showed that pectin had the highest tensile strength. In composite theory the strength can be increased with additional directional layering of the material. By adding bioplastics is was seen that the form of the material can be altered with 3D forming when given time to cure. The form can further be altered with pleating and folding while the bioplastic is still curing. When considering the life cycle of the material, using bioplastics supports Circular Design Theory. The material comes from a bio-based renewable source that is biodegradable at the end of its life and can become nutrients for the biosphere. As a bonus CO2 is removed out of the air in its creation. Finally, the bioplastic derived from alginate showed a unique quality in that it is water resistant and can be applied as a surface coating. It also exhibited a paper like quality, that allows its form to be manipulated like origami.

Figure [ ]: Bioplastic bonded to Interwoven samples, exhibiting changes in form during and after curing

Sensorial

When combined with bioplastics the sensorial properties were considered rough, fibrous, exhibited irregularity and had a heterogeneousness that illustrates an imperfect quality. The roots architecture and visible behaviour, shows traces of its growth, carrying the biography of the roots journey into the material.

Figure [ ]: Picture of pectin bio-composite illustrating the traces of growth

Affordance

The materials show the affordance potential of the roots to be manipulated into different pattern structures in the growing process. This can be utilised to symbolically represent the meaning of connection to nature by embodying patterns from nature. While still aligning to the novel imperfect aesthetic that would continue to be cognitive, affective and performative stimulation for users.

Figure [ ]: Picture of the roots affordance potential to be manipulated into a pattern

Performative

The rough fibrousness and the random interconnected heterogeneous effect of the roots elicited delicate interactions of rubbing, folding and pulling. Particularly to test the technical boundaries of the material; however the users did not dare to use any more strength for fear of breaking the material. This delicacy of interaction showed that people would treat the material with care, particularly knowing its origin. The perception of delicacy can be off set with the combined strength of a bioplastic and composite layering. However a balance should be met as there is potential here for enduring relationship with the material as is users treat the material with care to extend its life in product use.

Interpretive

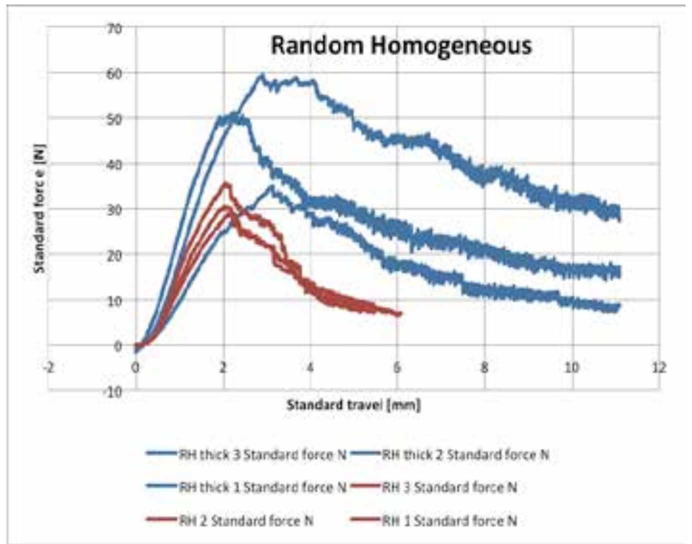
It has potential to express naturalness and to trigger evocative memories reminiscent to the past with deep connection to nature, a unique material experience to create richer and more enduring relationships (Rognoli & Karana, 2014). The imperfect qualities evoking naturalness and nostalgic interpretations are to do with memories of a time when we had a closer connection to nature. This aesthetic characterized by imperfection and the passing of time (Rognoli & Karana, 2014) is embodied through the biography of the roots. This leads to sustainable design as users care for the material. This is because perception of imperfection seems to be significant in users perceiving materials as natural or sustainable (Karana, 2012).

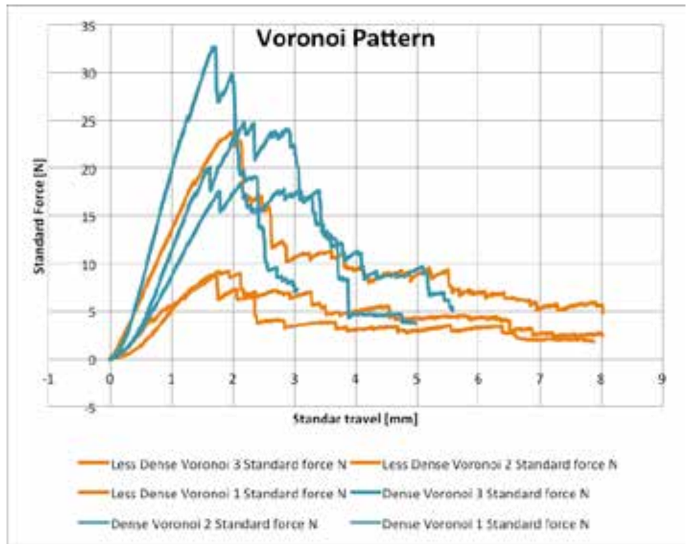
Affective

Users experienced intrigue with emotions like fascination upon first interaction, due to the unique and unfamiliar sensorial qualities, stimulating them to explore the material and root architecture. Sensorial pleasure was experienced through emotions like surprise, satisfaction and amusement at the incongruity of sense perception. Most noteworthy are the reflective emotions experienced once discovering the origin and its biography, evoking emotions such as, humility, kindness and pride. In regards to ideological pleasure associated to systemic reasoning for more environmentally benign materials. As well as feelings of care and connectedness to the natural world. This has potential to create longer lasting affective product attachment.

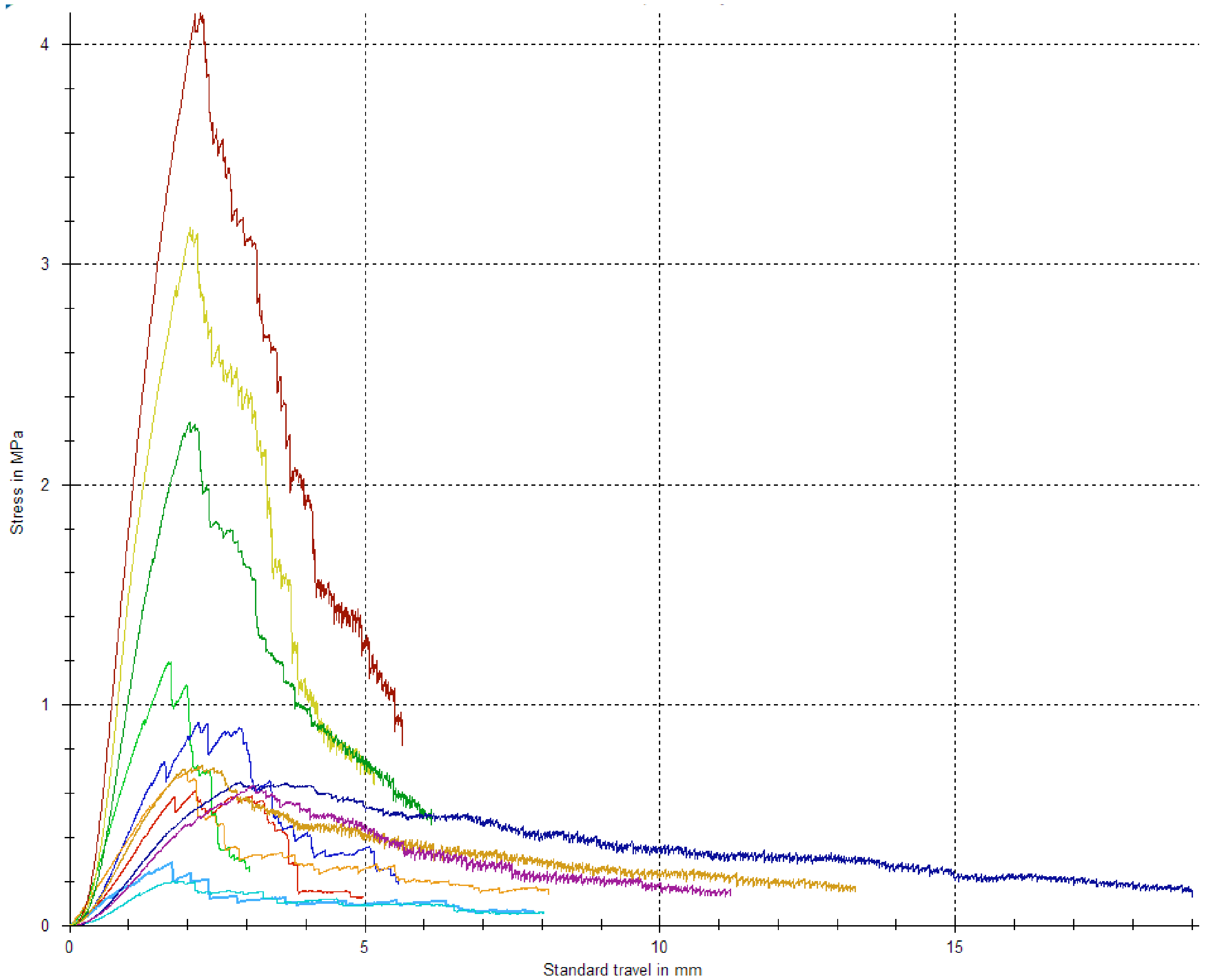
Tensile Results

Stress strain curves Interwoven samples





Stress strain curves converted to MPa



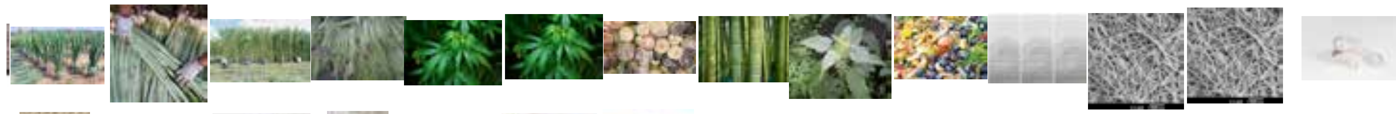
Appendix C

Benchmarking

Appendix C: Benchmarking

All natural fibre textiles

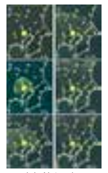
CELULOSE FIBRE TEXTILES											
Fibre type	Seed			Tree							
Plant	Cotton	Kapok	Coir	Lyocell	Pine needles	Areca Palm	Cork	Pine	Fig	Pine wood pulp	Mulberry tree
Plant picture											
Application Picture/ Sample											
brand	evan kinori	ingredients ldn	-	Simplifi Fabric	-	-	-	Studio Sarmite	-	-	Buro BELÉN
Designer	-	-	Jorrit Taekema	-	Tamara Orjola	Studio Tjeerd Veenhoven	-	-	-	-	Buro Belén
Project Name	-	-	Layer chair	-	Forest wool	Palm Leather	Cork Leather	Pineskins	Barkcloth	Lenpur	Wooden textile
manufacturer	-	Tensira workshop in West Africa	TU Delft	-	-	-	Sedacor JPSCORK Group	-	Dekodur GmbH & Co.KG	Filati Maclodio S.p.a.	-
Location	-	-	India, Africa	USA	Netherlands	Netherlands	Portugal	Latvia	Germany	Italy	Netherlands
composition	Organic cotton	Organic cotton cover & kapok filling	natural fibre extracted from the husk of coconut from + sprayed natural latex supplied by Enkev	Made from the natural cellulose found in wood pulp. Often mixed with Hemp, Cotton & Linin	Pine Needles & bioplastic binder	Areca Palm + Wood	Cork	Pine bark	sub-bark of the east African fig tree + high tech phenol- and aminoplaste papers	pure cellulose	-
End of Life	Biodegradable	Biodegradable	Biodegradable	Biodegradable	Biodegradable	briodegradable	biodegradable	Biodegradable			Biodegradable
technical properties	Heat resistant, absorbes water	hypoallergenic	Strong composite, water resistant	high absorbency, anti-bacterial, durable	Durable, hard, tough	resistant to tear, flexible, strength	durable, water resistant, stain resistant	water resistant, flexible, resistant to tear	UV, scratch, water, heat resistant	thermoregulator , breathable, anti-odour and absorbent, strong	Fexible, scratch resistant
experiential qualities	Comfortable, breathes	soft, silky, natural, snuggling	like silicone to touch, natural, organic, fiberous	natural, breathable, lightweight, soft, smooth	high-quality look and feel, fiberous	Leather like, natural fibre	smooth, soft, warm	surprises with its softness in contrast to the thick and harsh character	Smooth, hard, surface texture	Soft, similar to cashmere	Matte, soft, warm
applications	Clothing, Beding	Daybed bedding	chair / furniture	Clothing	carpet, paper, furniture	Upholstery, footwear	Apparel, upholstery, footwear	Apparel	Wall / ceiling panel, furniture	Sportwear, clothing, upholstery	upholstery, wedding clothing, funeral cloth
activities	Outwear, protection, decoration, styling, insulation, identity	comfort, warmth,	Load bearing, comfort	identity, comfort,	Decoration, load bearing, styling, insulating	Protection, decoration, comfort, identity	Protection, decoration, comfort, identity	decoration, identity	Decoration, protective, textile	Protection, comfort, textile	decoration, textile
ultimate purpose	Provide warmth	Bedding, comfort	Creating awareness on Natural Fibre Composites (NFC) in the domain of product design	Represents a milestone in the development of environmentally sustainable textiles	potential use of the billions of needles that normally go to waste	instigated as a cheap plant based replacement for animal leather, plastic and rubber.	Leather alternative	by-product of the wood industry can become more valuable. To challenge consumer mind set - skin only	Interior coverings	used in knit fabrics	interior textile
Process	-	-	The spun natural fibres are shaped into a fleece and sprayed with latex. The latex binds the curled fibres which are then pressed and vulcanised in several layers.	use of nanotechnology in an award-winning closed-loop process	crushing, soaking, steaming, carding, binding and pressing	dipping the dry and brittle leave from the Arecae Betel Nut into a biological softening solution	steamed and boiled to grant it extra elasticity. Then cut into thin sheets	Bark is pealed from imediately after tree is cut down, then treated with natural ingredients	Reinforced fibre textile, high pressure laminate. The bark is manually hammered soft into a flat fabric. The cloth is then pressed with high tech phenol- and aminoplaste papers under high pressure	-	Peeled from tree as skin. Soaked in solution, beaten with different tools to spread fibres and finally spread and massaged by hand.

Leaf		Bast							Fruit		Fungal		
Sisal (Agave)	Pineapple	Jute	Flax (linen)	Hemp	Hemp	Banana	Bamboo	Nettle	Fruit waste	Orange skin	Mycelium	Mycelium	Pure Mycelium
													
													
-	Pinatex	The future Kept	Libeco	Hippy Clothing	Hemp Bio Leather	Banana Paper	Mindsets Ltd	sorazora	FruitLeather	Orange Fiber	Mycoworks	Mylo	Mycotex
-	-	-	-	-	-	Matt Simpson	-	-	Koen Meerkerk (24) and Hugo de Boon	Adriana Santanocito	Phillip Ross	-	Maurizio Montalti & Aniela Hoitink
-	Pinapple Leather	Macrame Market Bag	Organic Linen	Hemp Linin	Hemp leather	Green Banana paper	Bamboo Linin	Nettle linen	Fruit Leather	Vegan silk	Mycoworks	Bolt threads	Officina Corpuscoli / Neffa
-	-	-	Libeco	-	-	-	-	-	-	-	-	-	-
Kenya / Tanzania	Phillapenes	Bangladesh	Belgium	UK	USA	Kosrae, Micronesia	UK	Nepal	Netherlands	Italy	USA	USA	Netherlands
Sisal fibre	-	Natural Jute	flax linen fibre	Hemp Fibre	Hemp fibre	Banana fibre + wax	Bamboo fibre	Nettle fibre	Mix of fruit waste fibre	Refined citrus cellulose	Mycelium grown on substrate food source	Mycelium, the underground root structure of mushrooms.	Mycelium gorwn in nutrient rich liquid substrate.
Biodegradable	Biodegradable	Renewable	Biodegradeable	-	-	biodegradable / recyclable	-	Biodegradable	Biodegradable	-	-	-	Biodegradable
Antibacterial, strength, durability, ability to stretch, resistance to deterioration in saltwater	Durable, strong, water resistant, flexible	strong, durable, absorbs natural dyes, light-fast, UV protection, sound and heat insulation, low thermal conduction and anti-static	non-allergenic, strong, durable	abrasion resistance/very durable, mold resistant, uv resistant	-	strong and natural water-resistant, highly fire and tear-resistant	anti-microbial, hypoallergenic and thermal regulating	similar to linen- but much stronger (it's strength even increases when wet) and a bit stiffer,	material is not strong enough and is not water resistant yet	Strong, durable,	strong, flexible, durable, versatile	strong, flexible, durable, versatile, abrasion resistant	Flexible, poor resistance to external forces
Natural, rough,	Leather like, natural fibre	lustre and uniformity of its fiber, shiny	Soft, dry, cool	Breathable, soft, natural	-	long lustrous fibers crisscross, smooth, natural, organic	Silky, breathable, good drape	natural, grainy, tiny irregularities , expressive	Transparent, grainy, warm colour, shiny	like a not greasy body lotion, silky	Leather like	Leather like	Transparent, hard & soft
Carpets, rope, furntiure, twines,buffing cloth, paper, mattresses	Apparel, clothing, footwear	Curtains, chair coverings, carpets, rugs, hessian cloth, bags, sacks	apparel linen, technical canvas, embroidery linen, clothing	apparel, canvas, shoes, upholstery, rope	-	Wallet, Bag, paper, canvas	Apparel, clothing, furniture	clothing, furniture	Bags, shoes, upholstery	Clothing	Bags, shoes, furniture	Bags, shoes, furniture upholstery	Clothing
Decoration, textile, protection,	Decoration, identity, textile, protective, fashion	protection, textile, packaging	decorative fabrics / textile, comfort	textile, comfort, protection	ootwear, apparel, automotive, transportation, interiors	Protection, decoration, packaging	Protection, comfort, textile	Textile, protection, comfort, identity	Textile, decoration, identity, fashion accessories	Textile, comfort, identity.	outwear, apparel, automotive, transportation, interiors	outwear, apparel, automotive, transportation, interiors	Textile, aesthetic,
Durable interior textile.	Leather alternative for fashion	Home decor, protection, packaging	Clothing and interior textile	outwear, interior textile	Leather alternative	advantage of waste stream and turn it into treasure. Help provide a living wage to Kosraean families.	Comfort, sustinable alternative	Textile	Textile - Transforming leftover fruits into durable, leather-like material.	utilise waste stream and propote social change in area of production	Alternative to standard narritive to making fashion items. Working towards recycling and circular fashion	Alternative to standard narritive to making fashion items. Working towards recycling and circular fashion	Alternative to standard narritive to making fashion items. Working towards recycling and circular fashion
leaves are crushed, beaten, and brushed away by a rotating wheel set with blunt knives, so that only fibres remain. Drying is important as fibre quality depends on moisture content.	-	fibers extracted by retting. The retting process is immersing them in slow running water. After the retting, stripping begins. In the stripping process, non-fibrous matter is scraped off.	flax is exposed to moisture to break down the pectins that binds the fibers together. Then combed, spinned, weaved & dyed	Same as Linen.	-	Fibre extracted from the stem with retting and then shearing on sharp edge roll. Fibres are dryed, cut, boiled and turned into pulp, then pulp is soaked in water on tray, then cold pressed.	No chemical modification - crushing the bamboo plant and then using natural enzymes to break the bamboo walls into a pulp. Fibres mechanically combed out and spun into yarn.	Cut, leaves removed, soaked, dryed, crushed and depithed, then brushed and spun.	Fruit is smashed, boiled, smeared, dried, and cut	The fiber, through nanotechnology techniques, is also enriched with citrus fruit essential oil.	-	They use corn stalks and supplemental nutrients to feed and grow our mycelium. They control growth conditions like temperature and humidity to encourage the mycelium to grow upward and self-assemble into an organized mat of interconnected cells. Then tanned like Leather.	The Universiteit Utrecht has developed a way of making floating mats of Mycelium. Mats then placed by hand directly onto manican body

Natural fibre textiles - Interwoven material family

Benchmark	Grown					Upcycled							Harvested				
Application process																	
Application picture																	
Brand	MycoTEX	Mylo	Mycoworks	-	BioCouture				Pinatex	Green Banana Paper	Fruit Leather	ReWrap	Tree Tribe	Folclore	Barktex	Studio Sarmite	Buro Belen
Designer	Aniela Hoitinik	-	Phillip Ross	Jen Keane	Suzanne Lee	Tamara Orjola	Tjeerd Veenhoven	Geneviève Levivier and the studio A+Z Design		Matt Simpson	Koen Meerkerk						Buro Belen
Technology	-	MycoFLEX	-	Microbial weaving	Fermentation	Forest Wool	Palm Leather			Banana tree		cocolok	Leaf leather	Cork Leather	Barkcloth or Kapa	Pineskin	Wooden textile
manufacturer	NEFFA, Officiana Corpuscoli, Mediamatic	Evocative & Bolt Threads	Mycoworks	-	-	-	-		Pinatex	Green Banana Paper		Enkev	Tree Tribe	Folcrore			
Composition	non-woven textiles consisting only of pure mycelium	100% pure mycelium	Mycelium grown on substrate	k.rhaeticus bacteria & yarn	Bacteria Cellulose	Pine needles composite	Areca Palm	Egg shells, flowers and PLA	non-woven textile of pineapple fibres	Banana tree fiber and wax	Waste mago fibres	Coconut waste + natural latex	Teak leaves sustainably sourced	Sustainably sourced cork bark	Mutaba tree bark	Pine bark	Mulberry tree bark
technical properties	Biodegradable, repairability	Strong, heat resistant, insulating, breathable, biodegradable	Durable, flexible, strong, biodegradable	Lightweight, flexible, biodegradable	Flexible, lightweight, biodegradable	Soft, biodegradable, durable	Durable, resistant to tear flexible, biodegradable	Biodegradable, lightweight, transparent, soft	Strong, durable, water resistant, flexible	strong, natural water resistant, fire and tear resistant	flexible, biodegradable, durable	Flexible, biodegradable, durable, water resistant	Strong, durable, and water resistant	waterproof, stain resistant and scratch resistant, durable, antimicrobial	Durable, water resistant, flexible, biodegradable	water resistant, flexible	flexible, scratch resistant
experiential qualities	Organic, natural, handcaft	Oragnic, Leather like,	Leather like, natural,	Transparent, modern, futuristic	transparent, natural, organic, strange, leather like	Fibrous, high quality, rough	Leather like, natural, warm, soft	Feminine, natural, modern, like stain glass window, meditative	Leather like, natural, soft, elegent	paper like, lustrous, smooth, organic and fiberous	Leather like, natural, grainy	natural, fibrous, simple, elegant, minimal	Natural, friendly, healthy	leather like, lightweight, natural, smooth	expressive, soft, supple	Soft, smooth, harsh, rugged	matt, soft, warm
applications	textile, clothing, lamp shades	Textiles, footwear, technical wear, upholstery	Textiles, upholstery, automotive, interior	Textiles, footwear	Apparel, textiles	interior, textile, insulation	Book cover, footwear, upholstery, interior, bags		footwear, upholstery, automotive, textile	assessories, textile	footwear, upholstery, textile	bags, textile	accessories, bags,	bags, accessories, upholstery	textile, clothing, upholstery	textile, clothing,	textile, upholstery,
ultimate purpose	Eliminates the steps of spinning yarns, weaving cloth, and sewing garments, thus taking out the costs, time, and energy this takes. Alternative to fast fashion.	produced in days versus years, without the material waste of using animal hides.	Alternative to leather	Alternative way to makes products of the future	Alternative to making textile of the future with less environmental and social impact	Upcycle of pine needles that normally go to waste	Cheap plant replacement for leather and rubber	between paintings and non woven art tapestries that act as example of beautiful circular textile	Alternative to leather	Turn waste into treasure from farming communites and provide alternative income and employment	Waste upcycle	upcycling food waste	plant based leather alternative made from tree leaves.	Sustainable source for textile material - same tree can be harvested every 10 years for over 200 years	CO2 - neutral, ancient tradition from Uganda and Hawii - UESCO heritage	By product of deforestation of pine forest	ancient craft of tapa-making is the cambium of the Paper Mulberry tree, a thin layer of fibers between the bark and the wood of the tree
Process	Instead, the fabric is stuck into a mould and shaped.	Corn stalks nutrients used to feed and grow mycelium. Control growth conditions like temperature and humidity to encourage the mycelium to grow upward and self-assemble into an organized mat of inter-connected cells. Then tanned like Leather.	-	Manipulate the growing process of the bacteria to use it in a new form of microbial weaving. The organism grows around the yarn inside a closed mould.	synthesize cellulose and ultimately grow a garment in a vat of liquid	Crushing, soaking, steaming, carding, binding and pressed.	Dipping the dry and brittle leaves into glycerol softening agent soultion before pressed flat.	-	The fibres are extracted from the leaves during a process called decortication. Fibres then undergo an industrial process to become a nonwoven textile. Pressed in Spain for leather look.	Fibre extracted from the stem with retting and then shearing on sharp edge roll. Fibres are dryed, cut, boiled and turned into pulp, then pulp is soaked in water on tray, then cold pressed.	Smashed, boiled, smeared, dried and tailored	made of fibre from coconut husks pressed together with a bit of natural resin.	leaves are soaked in water, dyed, then arranged flat together and set out to dry, which bonds the leaves and provides a large sheet of the leaf material. thin translucent outer layer made from a non-toxic BOPP film is applied that seals the leaf laye	Cork Oak tree is stripped, boiled in water, shaved down into very thin sheets, Cork is then glued onto cotton backing and pressed	Mutuba“ fig tree is harvested - produced with muscle power only, beaten and felted into large matt.	Bark is pealed, and treated with natural ingredients	Peeled from tree, soaked, beaten with different tools to spread and felt fibres and massaged by hand.

Manipulated Nature

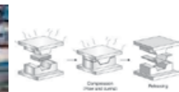
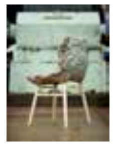
Application Picture/ Sample						 	
name	Full Grown	Research in Network Formation in Physarum Polycephalum	Square Watermelon	Sky Planter	Silk Pavilion	Living Architecture	Continuous Bodies – Bodies of Change
manufacturer	Full Grown Ltd.	Researchers: A. Tero, S. Takagi, T. Saigusa, K. Ito, D. P. Bebber, 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)
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
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	-
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
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
activities	decoration, function	-	show off; attract attention	decoration	exhibiting	exhibiting	exhibiting, showcase
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
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

						
ZERO Gravity	The Honey Comb Vase	Symbiosis	Living Root Bridges (locally known as jing kieng jri)	Water Based Digital Fabrication	Mycotree	
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
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
"...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
-	made by bees; sculptural; organic; slow	natural, delicate, careful, captive, changing with time	amazing, ingenious, natural, collaboration between human and nature	-	-	Comparable to foam, ligh
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
	containing flowers	changing with time; showing information; publicly captive	weight bearing		supporting	containing, protection
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 altern synthetic packaging
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 ar packaging shape. In the p and dehydrated, which ta mushrooms

Enhancing natural materials

ENHANCING NATURAL MATERIALS

Application Picture/ process						
Sample						
Brand	Studio Stefan Schwabe	-	-	Leaf	Truss Me	-
Designer	Jannis Hülsen	Jen Keane	-	Pedram	Sandeep Sangaru	-
Project Name	Xylinum Cones	This Is Grown	-	100% leaf plate	bamboo	-
manufacturer	-	-	-		-	-
Composition	Bacterial celulose	k. rhaeticus bacteria & yarn	Bamboo fibre strips	Palm leaves and paper made from the leaves	strong, solid, durable, lightweight	glass-fiber reinforced concrete (GFRC)
technical properties	high purity, strength, mold-ability, high absorbtion	strong and lightweight,	strong, lightweight	Light and stong	sustainable	Strong, light, bending strength
experiential qualities	sustainable transparent	transparent, modern	natural, patterns, unified	-	furnishing systems	Imitates stone
applications	-	-	Bags, stools, backets, furniture, upholstery	Table ware, packaging	enhancing of the material	Furniture, table tops
ultimate purpose	prove that biotechnological materials can feasibly become part of the production process of a variety of different materials.	grew the upper of a shoe to show how this could affect the way we make products in the future.	Aesthetic decoration and stability	food packaging and one-way dishes for outdoor tableware has to be fully renewable and fully biodegradable.	use of the locally resourced bamboo and skills in a sustainable fashion	Create a thin and strong structure
Process	Cellulose created by organically grown microorganisms, are grown in silicone moulds that are suspended and allowed to grow for 3 weeks, then dried.	Manipulate the growing process of k. rhaeticus bacteria, to employ it in a new form of 'microbial weaving'. The organism grows around the yarn that is weaved in a closed mould.	Two distinct sets of bamboo strips are interlaced at normally right angles to form an object.	Palm leaf stitched with leaf paper and leaf pressed with heat in aluminium mould.	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.	Build mould out of wood, seal it and apply the GFRC in thin layers and then compacting each layer with special rollers.

Application Picture/ process								
Sample								
Brand	Studio Kulla		Bas Froon	Christien Meindertsma	-	-	-	-
Designer	Adi Shpigel and Keren Tomer	marjan van aubel + james shaw	Bas Froon	Christien Meindertsma	Werner Aisslinger	Adital Ela	Nikolaj Steenfatt and Jonas Edvard	-
Project Name	50% saw dust	well proven chair	Biobased Babycarrier	The Flax Chair	monobloc chair	Terra Stools	Terroir	Artichair
manufacturer	-	-	-	Enkev	BASF	-	-	-
Composition	wooden sawdust and plastic bags.	Wood scrap and bio resin	Recurf material	four layers of an existing woven flax textile and five layers of a newly developed dry-needle felted flax.	Hemp fibres	earth and agricultural waste	seaweed and paper	artichoke thistle
technical properties	-	lightweight and moldable material	Strong, flexible	Extremely strong	High strength and low weight	Strong, rigid, biodegradable	tough and durable	Rigid, strong, biodegradable
experiential qualities	-	Chemical	Soft, composite, supportive	-	-	Dark, natural, organic	Warm and tactile, and the lightness of paper	Organic
applications	furniture and lighting	Furniture	Baby carrier, accessories, interior coverings	Furniture	Furniture, shelving	Furniture	Furniture	A coffee table, a lounge chair and a dining chair - furniture
ultimate purpose	Research, and the development of new design methods, offering new ways of experiencing everyday products.	-	bring back industrial production of labour-intensive 'soft' products to local manufacturers	affordable, scalable, environmentally friendly, locally made product whilst exploring a new production processes	BASF's water-based acrylic resin Acrodur® with new material and old tech	Repurpose agricultural waste	New manufacturing technique	Taking advantage of unseen potential within this developing industry - response to the current economic crisis in the designer' s native Greece,
Process	mixture of the two materials is pressed into an aluminum mold and then baked. The heat creates a homogeneous connection without using any adhesives.	wood scraps, and bio resin react, expand like foam, with the addition of water, and increased temperatures these different factors can give expansion of up to 600-700%	'micromoulding' machine that makes it possible to locally change material qualities from a velvety soft material into a strong	The soft pile of fabrics is heat pressed, melting the flax and PLA into the shape of a rigid chair.	industrial process of compression molding at low-cost mass production, method releases no organic substances such as phenol or formaldehyde during the cross-linking process.	Compressed in mould	seaweed is harvested along the beach of Denmark. After being dried the seaweed is ground into powder and cooked into glue, utilizing the viscous and adhesive effect of the Alginate. Compressed	Artichoke thistle fiber reinforced plastic - artichoke thistle fibers and a biological resin in a compression molding process.

Appendix D

Pattern Type Research and structural results

Shapes

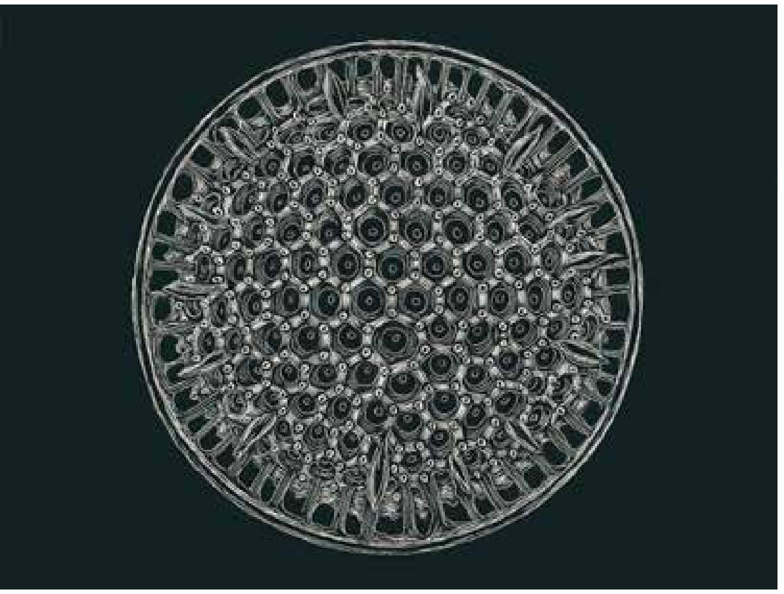


Figure [ ]: Radiolarian Aulonia Hexagona (Brodie C., 2005)

Figure [ ]: Spittle Bug blows a bubble fortress to protect its self in Spring (BBC, 2019)

Figure [ ]: Photo by Matthew T Rader on Unsplash

Face to Face Shapes

Bubbles

In nature bubbles composed of soap films, occur on a microbiological level as well as on larger scales. Bubbles form spheres with a surface with a minimal area i.e. the smallest possible surface area for the enclosed volume (Ball P., Shapes 2009). When two bubbles of different sizes meet, they create a convex shape at the point of connection (a), because of differences in gas pressure. When three meet, the vertices form angles of exactly 120°, provided that each of these bubbles contain the same volume (b), and when four meet they rearrange its self so three walls meet at any point (d). See figure_ below.

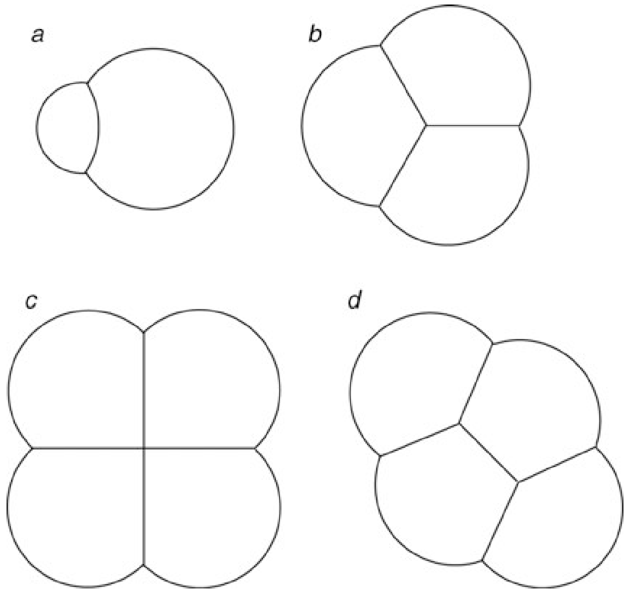


Figure [ ]: Combination of bubble vertices

Pattern follows form

When many equal bubbles form they create a pleasing stable lattice structure of regular geometric order that is symmetrical and balanced, packed together in an identical and constant tessellation of polygonal uniformity.

On a macro scale the honeycomb structure is a near perfect example of this in nature, as *"workers secrete wax from their abdomen, which is pulled out using their hide legs and then chews to make the wax mould-able, each softened flake is placed one-by-one, so the comb is made like we construct a brick wall"*, (Ball P., Shapes 2009). Another examples of this at a micro level is microbiological lifeforms like radiolarians, exoskeletons are formed by blowing bubbles around their soft tissue, forming impressive patterns of, in the case of the radiolarian Aulonia Hexagona, a sphere (seemingly) comprising entirely of hexagons. Figure [ ].

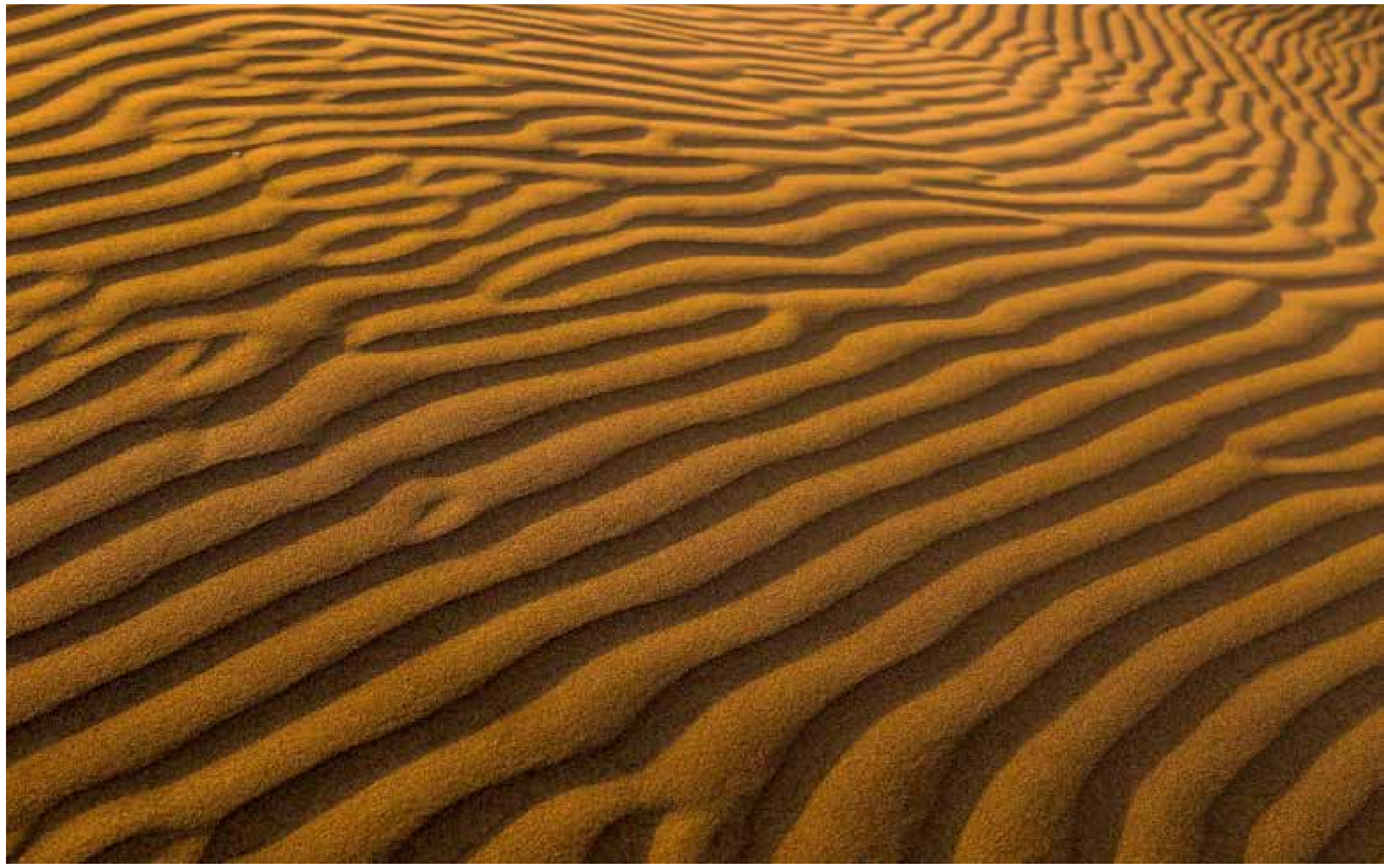


Figure [ ]: Photo by Jeremy Bishop on Unsplash

Foams

An interesting phenomenon that happens with soap films, is that when they begin to dry they transform from spherical packed balls towards polyhedral forms of pentagons having different lengths and corners of different angles and differing organic quality, see figure [ ]. This is formed by bubble mechanics, i.e. Plateau's laws describing surface tension and Plateau borders. (Ball, P., Shapes 2009)

They retain geometric regularity but it becomes disorderly, lacking obvious principles and organisation, seemingly, a random and haphazard cellular-like arrangement of unequal structure, sitting more or less even distances apart and often with round edges.

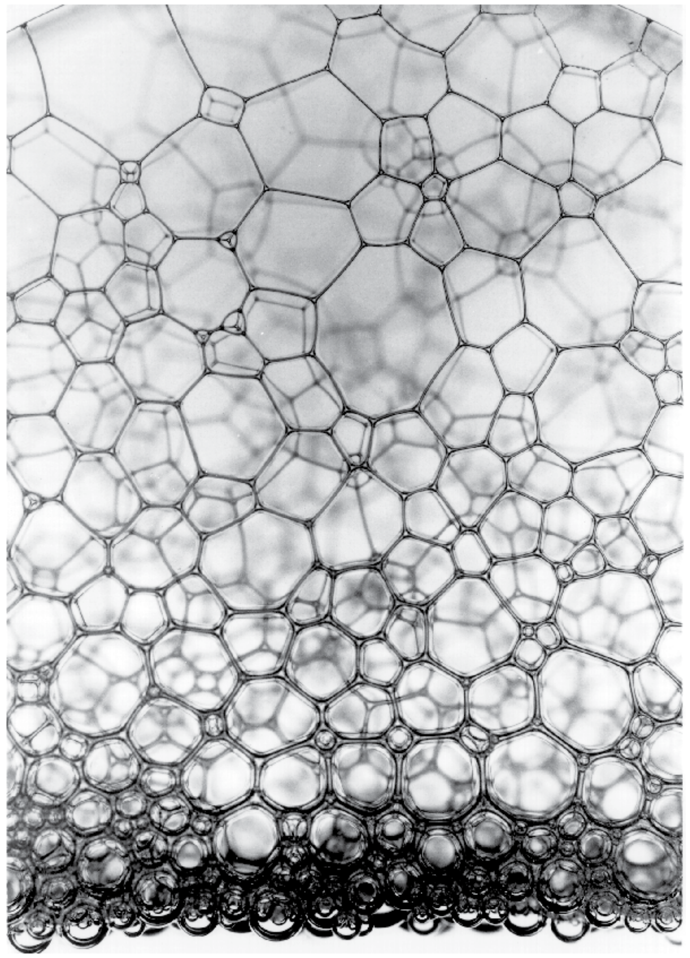


Figure [ ]: Wet foam to dry foam (Picture by Hutzlerr. S 2015 - structure and energy of liquid foams.)

Figure [ ]: Photo by Louise Pilgaard on Unsplash

Voronoi patterns in dragonfly wings (Photo by Jack Kaminski)

Voronoi
A noteworthy form of this kind of face to face tessellation discussed in the previous paragraph is the Voronoi pattern. Named after Georgy Voronoi, and used to model cells, or biological micro-architecture. They work as *"a geometrical tool to understand physical constraints that restrict the growing of biological tissue in specific ways"* (Sanchez-Gutierrez et al., 2016).

They consist of points on a plane, that are connected to all of their closest surrounding points. It is geometrical way of dividing space into a number of regions or cells to balance out tensions and forces within tissue, so that structures can be formed, like the wings of the dragonfly in figure [ ].

The construction of Voronoi cells can be explained by evaluating a set of random points (n) on a canvas. The red dots, labelled n1 to n3 represent these points. When connecting these points, and intersecting them perpendicularly halfway through, these lines will meet in crossing c, forming the boundary between these points. See figure [ ],

These patterns can often be seen on a micro level in cell structures, and on a macro level on a giraffe's body. See figure [ ].

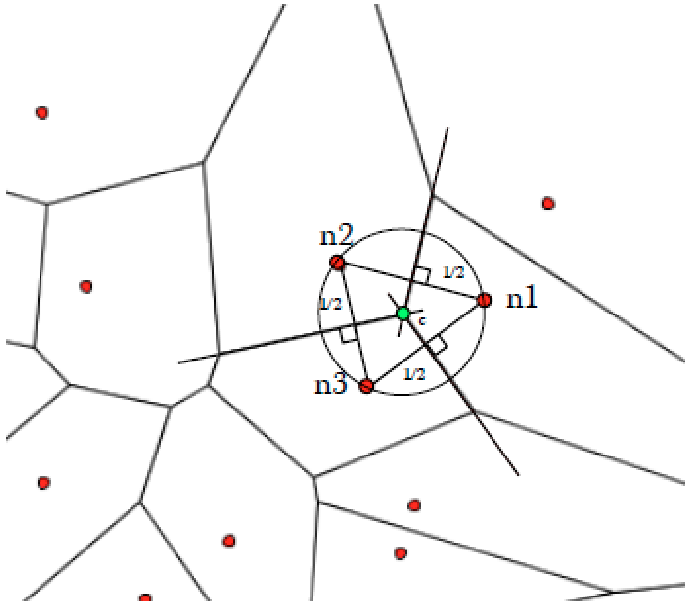


Figure [ ]: Construction Voronoi cells. Image courtesy of Gijs Louwers

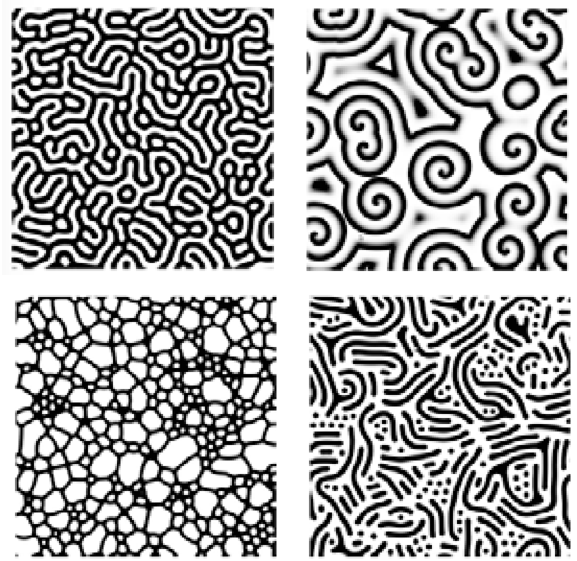
Reaction Diffusion
Reaction Diffusion systems represent one of natures most widespread and versatile processes for producing patterns.

In 1952, mathematician **Alan Turing** proposed a theory to explain a series of patterns that occur throughout the natural world. His fascination for embryology and the way in which an embryo develops into a full human being led him to conclude that there had to be some mathematical principle underlying it all. In his paper, *The Chemical Basis of Morphogenesis (Turing A., 1952),* he proposed that the diversity of patterns we see in nature can be explained by a mathematical model, called the *reaction-diffusion system*.

He considered that during an organisms development genes in different cells might be switched on (activated) or off (inhibited) by chemical agents called *morphogens,* that diffuse through tissue. As these morphogens diffuse through the embryo they cause the cells around them to transform, ultimately creating patterns like spots, stripes, spirals, hexagons and whirls.

Morphogens are in essence opposing forces that cause a symmetry. However, for a reaction to happen, morphogen A needs to promote the formation of morphogen B, that in turn inhibits the formation of morphogen A. Morphogen A, activating the reaction, is in this sense *autocatalytic*: the rate at which morphogen A is generated depends on how much of morphogen A is already present, (Ball, P., Shapes, 2009). One of these morphogens then acts as a catalyst.

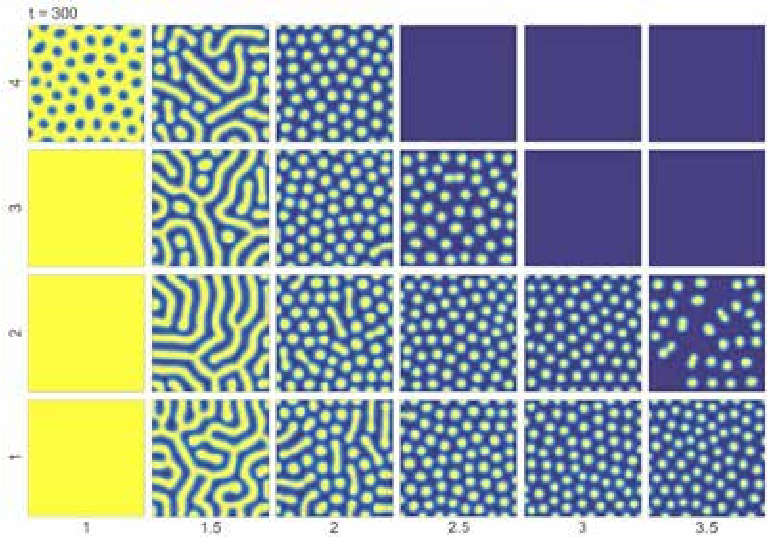
Note: Keep in mind that Turing patterns are one of the many types of activator - inhibitor systems that appear under specific conditions.



To indicate a macro example of these patterns occurring in nature, look at figure [ ] showing grass in the Negev Desert in Israel. Plants requiring a lot of root space distribute themselves at an optimal distance from their neighbours, following a similar reaction-diffusion process. These grass boundaries grow in scarce water environments, which is why these plants are specialised on retaining water. A clump of grass becomes an *activator* of more growth because it blocks the water, while preventing water to flow to areas directly downhill from it. In this sense it also *inhibits* its surroundings, creating the dry patches in between.

Modelling Reaction-Diffusion
The mathematical model for predicting these patterns is complex to say the least; however we can generate *Simple Turing Patterns* based upon the *Gray Scott Model* of reaction diffusion, which simulates two virtual chemicals reacting and diffusing on a 2D grid that generates spatial patterns from almost uniform initial conditions, see figure [ ].

Very complex and dynamic behaviours can arise from the Grey Scott Model simulation. The reaction naturally has two stable states: lots of A with no B to consume it, or lots of B where new A is quickly converted into more B. But the diffusion can cause interesting behaviours at the borders between the mostly-A and mostly-B areas, as illustrated below in figure [ ].



A Typical Turing Pattern, which is top left of figure [ ], can be described as a succession of meandering or flowing stripes or irregular shapes that are evenly spaced and repeating. Each elements or form is similar, but not identical and repetitively changes randomly in a seemingly disorderly way that has little regularity as the trajectories mutate. They lack symmetrical structure and illustrate higher entropy.

Figure [ ]: Oscillating chemical reaction (Photo by Stephen Morris)

Flow

Flow is present in many aspects of natural patterns. The way in which particles move, subjected to internal forces is described here. There are other processes within this theme; however they were deemed out of scope for this project.

Belousov - Zhabotinsky reaction

Spirals and Waves

A form of a reaction - diffusion pattern, belonging both to the *Shapes* as well as the *Flow* theme, is the Belousov-Zhabotinsky reaction. This chemical reaction, first observed in the 1950s by Belousov, a Russian biochemist, was considered impossible when it was first discovered, because it was thought that it went directly against the second law of thermodynamics "which determines the direction of all spontaneous change in the universe, says that closed systems always evolve towards states of higher entropy" (Ball, P., 2009).

However; this oscillating chemical reaction, as shown in figure [ ], rather than moving towards entropy, meaning that all particles are diffused in the medium like a drop of ink in water, it changes colour at regular intervals over and over again.

When specific concentrations of a chemical are added on specific locations, it creates a visible effect of increasing wavelike patterns. The wavelike behaviour of this reaction is described as a periodic pattern. Because of the autocatalytic nature of reaction-diffusion patterns, as described previously, small differences in concentrations of chemical a or b can create spiralling or concentric waves, as seen in figure [ ].

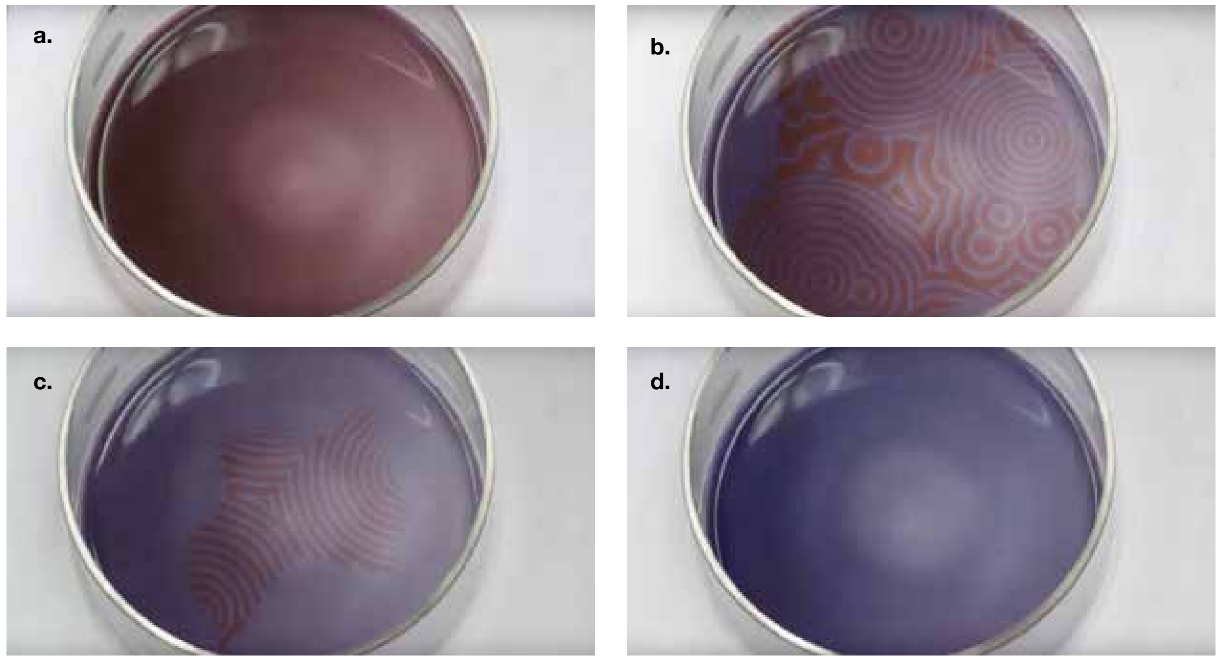


Figure [ ]: Continuously repeating stages (a) to (d), moving from red to blue and back (Footage by Stephen Morris)

Branches

Growth in nature occurs along mathematical guidelines for self-repetition and through the copying of beneficial connections between elements, form specific networks along which the whole system benefits. Of particular interest in this theme is a model called *DLA branching.*

DLA branching

The fractal nature of branching networks occurs at many different scales, including river networks, plants and trees, root systems, bronchial systems and cardiovascular systems.

The *diffusion-limited aggregation* (DLA) model, as seen in figure [ ] was developed in 1981 and describes the way in which particles clump together the moment they touch, involves that particles "are added randomly to a growing cluster from all directions", (Ball P., Branches 2009). A property of DLA patterns is that they look the same on different levels of scale, similar to a river and a leaf vein network.

The structure of river networks is visually comparable to the random branching veins of leaves at a small scale. The branching structure of river networks can be described with *DLA branching,* while it is "less clear about the origin of the branching in leaf veins; however they are optimal for transporting nutrients to all parts of the leaf wit the least total resistance", (Pelletier, J.D, et al, 2000).

The figure [ ] to the right illustrates how slime mould is also similar to the network of a river and the veins of leaf architecture. Each image exhibits *self repetition* at different levels.

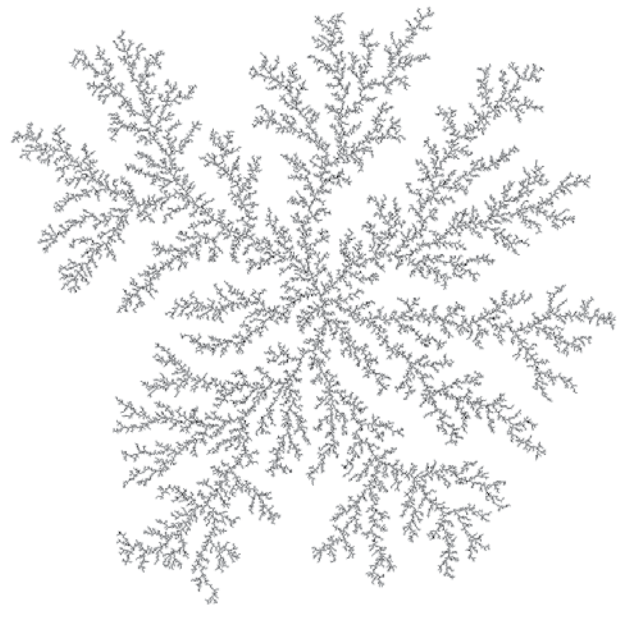


Figure [ ]: DLA branching simulation (Paul Bourke, 2014)

In the previous paragraphs you have been introduced to the fractal nature of patterns and there propensity to display regularity, order and structure. In addition the pattern types have been categorised and assigned based on three main themes: *Shapes, Flow and Branches*, and the way in which these patterns are formed in nature was discussed.

Conclusion

Nature constructs the most intricate patterns, through complex physical and chemical processes, which can be described in the words of Philip Ball *as "a palette of principles."* (Ball P., 2009 p.180 Branches), found on different scales, from macro to micro levels, and thanks to many noteworthy scientists, can be boiled down to a set of rules, which we can use to simulate our own patterns or simply learn to appreciate and draw inspiration from the aesthetic or structural beauty of nature.

Figure [ ]: Self repetition at different levels in nature, from left, slime mould, a river delta and the skeleton of a leaf

Below are representations of the pattern types cut out of wood and stacked on top of each other to visualise the patterns. Like in nature the patterns have been stacked in a fractal way, each representing a self similarity at different scales. Additional terms have been extracted from the previous research in order to have key terms to describe the patterns.

Face to Face: Polygons

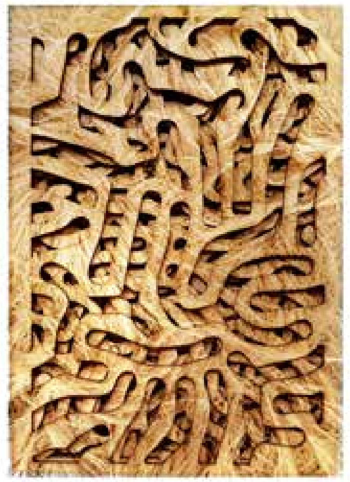
Key Terms
- equal
- uniform
- lattice structure
- regular geometry
- ordered
- symmetrical
- balanced
- packed
- identical
- tessellation
- polygonal
- heterogeneous
- Stable

Key Terms
- irregular
- non-uniform
- disorderly
- less organisation
- inconsistent sizes
- inconsistent shape
- random distribution
- cellular-like
- unequal structure
- even distances
- round edges
- heterogeneous

Ordered, uniform, regular ⟷ **Disordered, non-uniform, irregular**

Meandering Lines

Key Terms
- little regularity
- non-uniform
- meandering
- flowing
- little organisation
- inconsistent sizes
- inconsistent shape
- random distribution
- unequal structure
- even distances
- homogeneous
- mutate
- disorderly
- high entropy



Key Terms
- branching regularity
- non-uniform
- meandering
- flowing
- organised
- inconsistent sizes
- consistent shape
- random distribution
- equal structure
- even distances
- homogeneous
- high entropy

Irregularity, unequal, random ⟷ **Regularity, organised, random**

Bag sample made with 3 layer of interwoven

Upclose image of the hexagon bio-composite

	Maximum extension	Test speed	Pre-load	Specimen no.	h	b	A_0	Peak detection	Date/Clock	$L_{0\,CH}$
	mm	mm/min	N		mm	mm	mm²	N		mm
1. Hex 1lyr	10	2	0.1	1	0.89	35	31.15	23.07990837	43801.5	76.3272
2. Hex 1lyr	10	2	0.1	2	0.89	35	31.15	20.75686646	43801.5	73.29542
3. Hex 1lyr	10	2	0.1	3	0.93	35	32.55	25.74694633	43801.51	67.82435
4. Hex 1lyr	10	2	0.1	4	0.94	35	32.9	24.24934959	43801.51	71.74947
5. Hex 1lyr	10	2	0.1	5	0.97	35	33.95	19.21575356	43801.52	75.44748
1. linear 1lyr	10	2	0.1	11	1.25	35	43.75	44.63039398	43801.57	76.23128
2. Linear 1lyr	10	2	0.1	12	1.25	35	43.75	45.0644455	43801.57	73.51303
3. linear 1lyr	10	2	0.1	13	1.25	35	43.75	59.85347366	43801.58	73.37139
4. Linear 1lyr	10	2	0.1	14	1.35	35	47.25	72.11103821	43801.58	76.68782
5. Linear 1lyr	10	2	0.1	15	1.35	35	47.25	80.51300812	43801.58	70.96577

Results of the single layer bio-comosites

	Maximum extension	Test speed	Pre-load	Specimen n	h	b	A_0	Peak detection	Date/Clock	$L_{0\,CH}$
	mm	mm/min	N		mm	mm	mm²	N		mm
1. Linhex 2lyr	10	2	0.1	6	1.45	35	50.75	57.0335312	43801.53	88.59627
2. Linhex 2lyr	10	2	0.1	7	1.23	35	43.05	65.2643127	43801.54	88.27653
3. Linhex 2lyr	10	2	0.1	8	1.23	35	43.05	64.0421906	43801.55	89.67721
4. Linhex 2lyr	10	2	0.1	9	1.23	35	43.05	71.218399	43801.56	87.66968
1. Hexhex 2lyr	10	2	0.1	16	1.12	35	39.2	39.3961983	43801.59	87.00764
2. Hexhex 2lyr	10	2	0.1	17	1.12	35	39.2	60.2677689	43801.59	79.83946
3. Hexhex 2lyr	10	2	0.1	18	1.05	35	36.75	46.8989182	43801.6	80.69825
4. Hexhex 2lyr	10	2	0.1	19	1.05	35	36.75	28.1371231	43801.6	83.6093
5. Hexhex 2lyr	10	2	0.1	20	1.05	35	36.75	38.2775269	43801.61	85.83904

Restults of the double layer bio-composite