Biofibrous Potentialities:
A Scalar Approach to Biogenic Futures

by

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Dalhousie University is located in Mi’kmaq’i,
the ancestral and unceded territory of the Mi’kmaq.
We are all Treaty people.

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Abstract

Our current extractive practices with architectural materials are unsustainable and biogenic options must be explored. Much of the current discourse and use of biogenic materials in architecture operates as a one-to-one replacement for existing material typologies. However, there is an emerging interest in exploring these materials using contemporary digital fabrication tools. One biogenic material option is the by-products of flax production. The climate in Nova Scotia is suitable for sustainable growth of fiber flax, and there is a growing resurgence of this industry, and an interest in supporting it with a circular economy. The by-products currently do not have a specified use and are a prime candidate for exploration as architectural materials. Additive manufacturing, commonly referred to as 3D printing allows for customized, locally sourced, surplus free design possibilities. Using this fabrication method this thesis uses an emergent scalar approach to explore a biogenic material future.

Acknowledgements

I would like to thank my supervisor James Forren for introducing me to the world of biomaterials and fabrication in my first Master's studio. Additionally, thank you for allowing me to complete this messy investigation in the MBE lab space. I would like to thank my advisor Jennifer Green for your support and for welcoming me into the world of Flax in Nova Scotia. I would also like to thank Catherine Venart for your support and guidance in untangling and entangling my ideas in the first semester of this thesis.

Thank you TapRoot Fibre, for providing by-products and welcoming me into your facilities.

To my partner for your unwavering support and for coming along on this journey with me. To my family, thank you for all your love and encouragement.

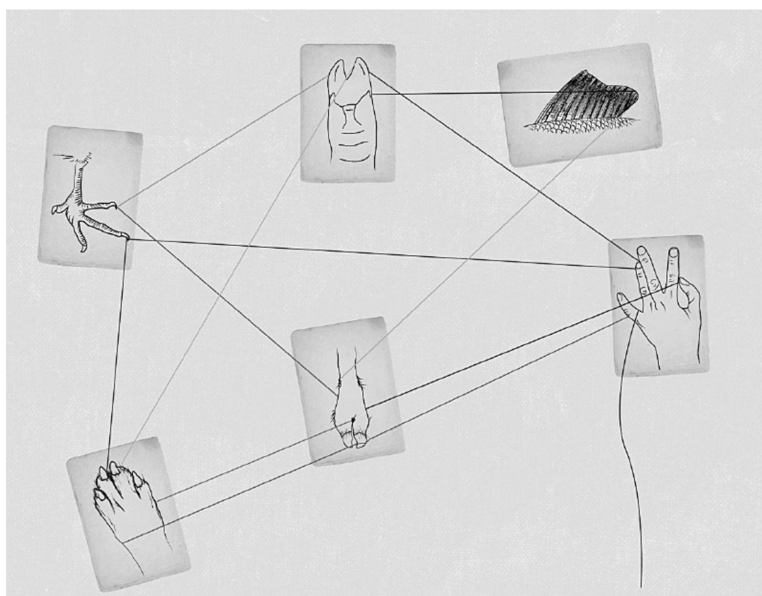
Chapter 1: Introduction

We are in constant visual and tactile relationships with the materials in our natural and constructed environments. When formulating this thesis, the primary influences were a personal interest in natural/biogenic materials, a desire for hands-on material engagement, digital fabrication, and textiles.

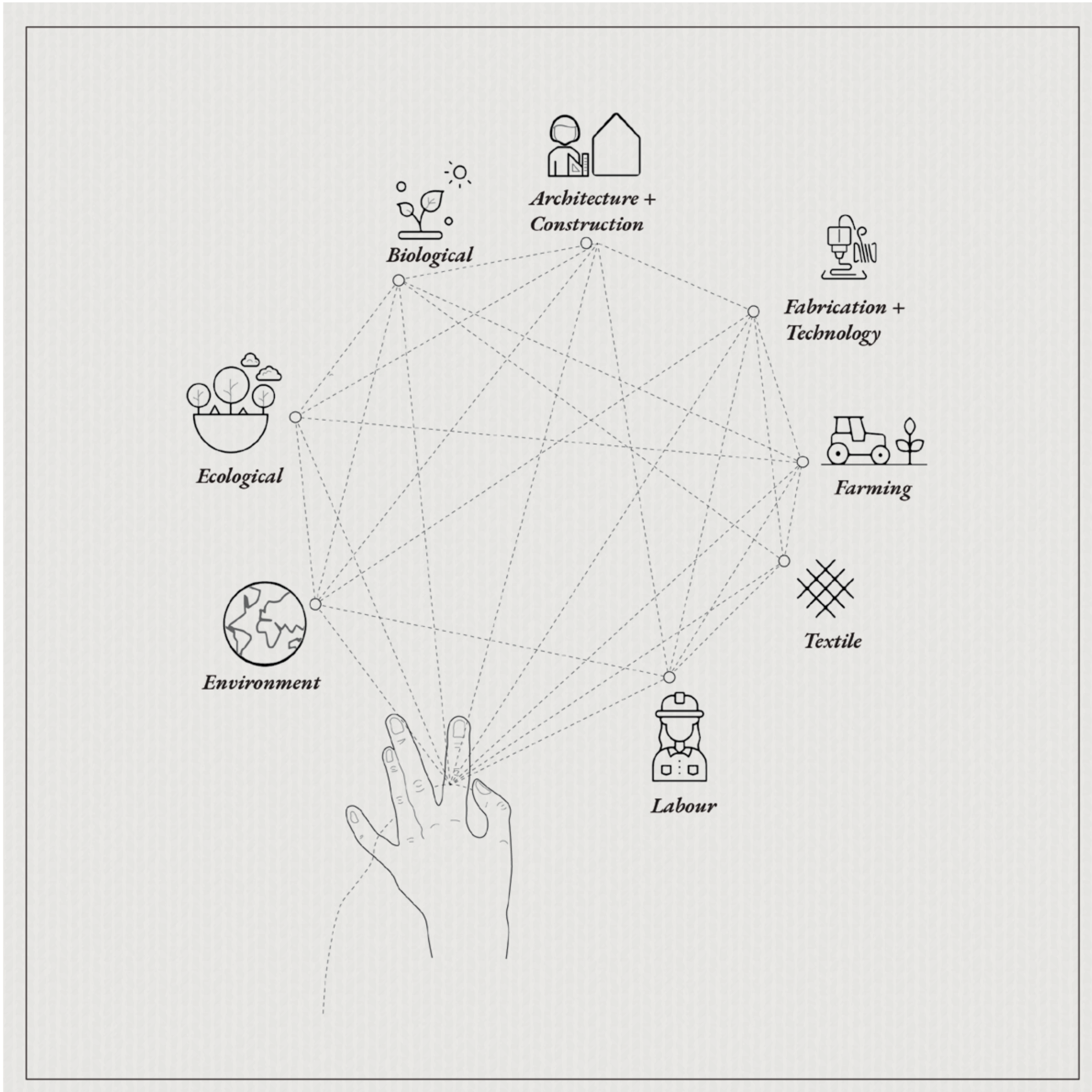
In researching local and natural material options, an introduction to a resurgent linen industry in Nova Scotia shifted this thesis from textiles to their by-products. This industry has an abundance of flax by-products in need of use to meet its circular economy goals.

String Figure Frame

As architecture seeks to intersect and position itself across multiple scales, intersectional frames are attractive and necessary. One method to address systems influx is Donella Meadow's writing on systems theory (2008). This method



Multispecies Cat's Cradle. Drawing by Nasser Mufti, 2011. (Haraway 2016)



String figure diagram of human and non-human actors related to thesis inquiry. (Images from Mufti 2011 and Noun Project 2022).

considers the feedback loops between connections in a system for problem-solving (Ibid.). For Meadows, a system emerges by observing, charting, and adjusting a system. In an architectural context, Kiel Moe encourages architects to think beyond their traditional restrained Cartesian Frame of Reference and work towards a Lagrangian Frame of Reference (Moe 2019). A Lagrangian Frame observes multiple objects in motion and has a plastic boundary that shifts over time. This thesis draws ideas from Donna

Alberta Oil Sands #9
(Burtynsky 2007)

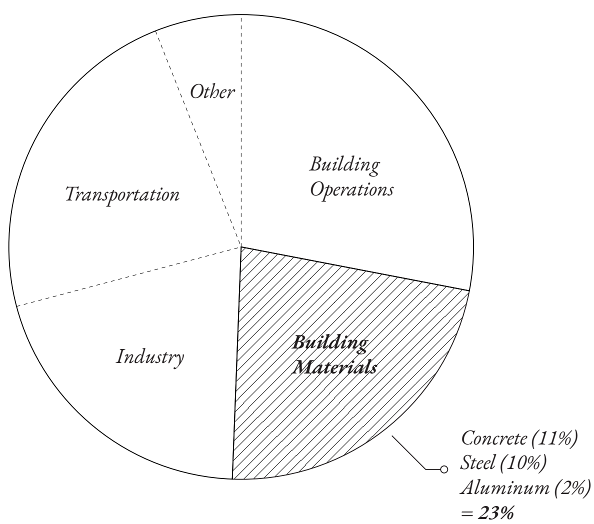
Clearcut #4
(Burtynsky 2016)

Rock of Ages #7
(Burtynsky 1991)

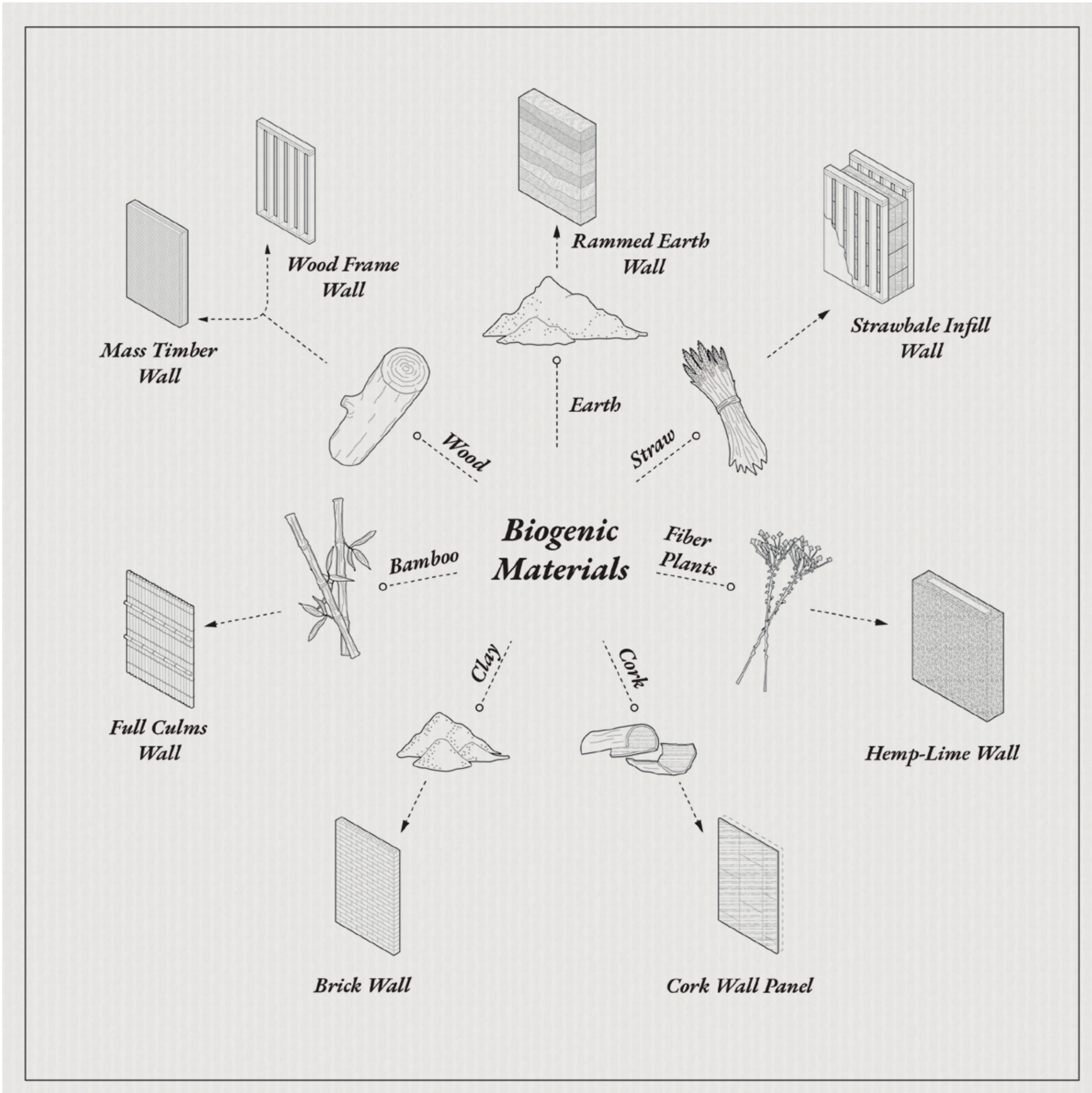
Haraway's writing on string figures. She uses these familiar games as a way to describe how multiple actors, both human and non-human, can, recuperate and efficiently move forward together to form new worlds (Haraway 2016, 10). This method of thinking establishes a fair and reciprocal dialogue between human and non-human actors constantly in a game of giving and taking, moving and adjusting, and destabilizing and equalizing.

From Globally Extractive to Grown

Due to the growing concerns and consequences of the growing climate crisis, the global consciousness of the architectural field is shifting towards prioritizing reducing carbon emissions in the industry. Architecture's customary and habitual modernist-dominant materials like concrete, steel, glass and aluminum produce nearly a quarter of annual global CO_2 emissions (Architecture 2023 2022). Petrochemical industries also contribute to global carbon emissions, and, through leaching and microplastics, have infiltrated our air, water, soils, and bodies. While these



Architectural Materials contribution to global Embodied Carbon
(data from Architecture 2030 2022)



Graphic showing common biogenic materials and their typical uses. (Examples shown in graphic are informed by Lewis 2022)

materials claim recyclability as an offset to their harmful effects, most materials end up in a landfill if the recycling resources are unavailable or limited; these are finite, non-renewable landscapes that negatively impact human and non-human health, and draw minimally from locally available materials. Ultimately, these materials are not sustainable, and alternatives must be explored. These alternatives must eliminate or drastically reduce our reliance on unsustainable, destructive, and carbon-intensive materials and production methods.

The current alternative landscape reprioritizes using materials grown or created by living organisms, known as biogenic materials. These materials sequester carbon from the air and are a regenerative and renewable material resource in our human time scale. Biogenic materials and architecture have an interconnected and extensive historical relationship that is being revived, aided by contemporary digital fabrication tools, material science and necessity. Typical biogenic material use substitutes an extractive option, such as steel, with a biogenic option, like mass timber. However, though popular and situationally viable, timber is not the only biogenic building option. Each biogenic material offers unique possibilities that emerge from its individual and unique growing characteristics. Carbon-conscious structural engineer Bruce King suggests an alternative feedstock of biogenic materials: agricultural residues or by-products (King 2017; King and Magwood 2022). These are diverted from the waste stream and given an architectural material purpose (Ibid.). These include waste fibres and stalks, and one such material is Flax.

A Local Agricultural By-product

Flax is a tall, slender plant grown purposefully for its long, strong, hydrophilic blond fibres for weaving linen textiles. In Nova Scotia, there is a resurgence of the fibre flax industry rooted in an interest in farmers diversifying their crops, as well as a desire for materials to create a locally produced textile craft. Although flax is not indigenous to Canada, it has historically been grown in Nova Scotia by settler colonialism. This thesis acknowledges that the materials which are so central to this thesis, were grown from the soils in Mi’kma’ki, the unceded and ancestral territory of the Mi’kmaq people. Flax is well suited for the climate and can be sustainably grown without additional irrigation or fertilizers. There are fifteen farmers dedicated to learning to grow the plant through The Flaxmobile Project, and an organic farm, TapRoot, that has developed a mechanized processing system. In these initiatives, there is desire and momentum to build up this economy circularly, which creates an opportunity to explore options to utilize the resulting by-products.

Thesis Question

This thesis explores the potential of industrial fibre flax by-products as a novel biogenic architectural building material. It combines methods of making, biomaterial exploration and additive manufacturing to build a printed component typology informed by three design elements: columns, walls and enclosure. This results in an architectural demonstrator that explores this material’s limitations, opportunities and tactility in a quest for a Biogenic Future.

This thesis uses a multi-scalar method of design and investigation. It reacts to global ideas and concerns about architectural materials explored through digital fabrication. The second chapter develops and outlines the scalar method of this thesis. The tree scales of the method are global, local and material. The third chapter provides relevant background on the raw material and additive manufacturing method. Chapter four outlines the technical process of taking a by-product and preparing it for printing. It provides an outline of the material dialogue process and summarizes the specific protocols of this material. Chapter five builds on this knowledge of how to work with this material and tests it against three architectural elements: a column, a wall, and an enclosure. Prototypes of each printing language for these elements are created and applied to prints. Chapter six applies a printing language to an architectural demonstrator. Lastly, this thesis concludes by reflecting on this process and ideas to move this work forward.

Chapter 2: A Scalar Method

This thesis uses a multi-scalar method of inquiry to explore a global concern in a local context, through a material investigation. Rachel Armstrong, a proponent of Experimental Architecture and Living Systems, emphasizes the importance of architectural research and experimentation's "wicked" character "that bring[s] different agents together in attempt to address the uncertainties of a hypercomplex world" (Armstrong 2021, 40).

Making Material

At the core of this thesis method is a material investigation of an agricultural residue that is a local version of a biogenic material (King and Magwood 2022). This thesis uses biomaterial methods of exploration. The current biomaterial landscape is mainly in a craft and maker space. Biomaterials use organic and natural materials and are easily made with standard tools. This community relies on open-source sharing through sites like Materiom (Materiom 2023). Approaches to making are largely tied to craft, but how does one begin a material investigation where there is little to no existing craft to draw from? Anthropologist Tim Ingold studies at the intersection of the four A's: anthropology, archeology, art and architecture. He provides a method of a material-driven design approach that he terms the "Art of Inquiry"

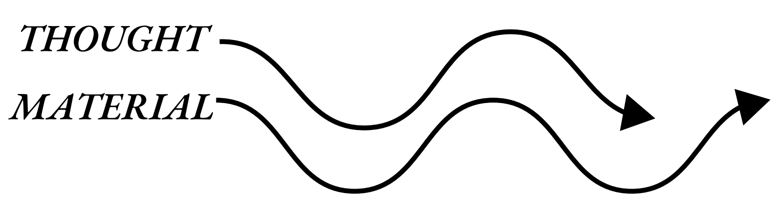


Diagram showing Tim Ingold's Art of Inquiry. "The conduct of thought goes along with and continually answers to the fluxes and flows of material." (Ingold 2013)

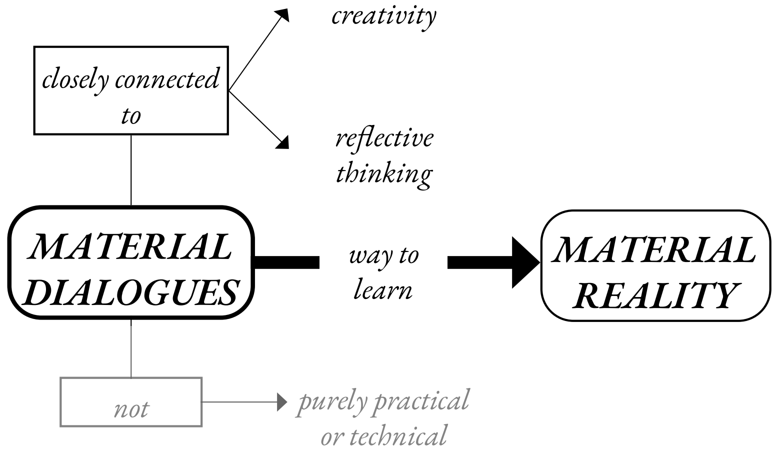


Diagram of Mette Bak-Andersen's Method of Material Dialogues (Bak-Andersen 2020)

(Ingold 2013). Here, material and thought move together, and the material informs thought rather than the reverse (Ibid.). Ingold's method stresses the importance of tacit learning in engaging with the material. It highlights that the material investigation will better inform a design than a mere speculation about the material can. In a similar ideological approach to materials as Ingold, Mette Bak-Andersen's method of Material Dialogues provides a method of working in dialogue with new sustainable materials (Bak-Andersen 2020).

Flax Precedents

Three categories of current investigation emerged in researching the current landscape of flax fibre and its by-product material investigations: artistic inquiries, composite utilization, and biogenic futures. An example of artist inquiry is *A Flax Project* by Dutch designer Christien Meindertsma. The artist purchased a plot of land and 10,000 kilograms of flax fibres. She intended "to find out if the harvest could be locally processed into an environmentally friendly textile"

(Meindertsma 2010). In addition to her textile explorations, she completed extensive projects with the by-products, including creating different linoleums from the seed oils, powders and burnt ash from anaerobic digestion and a chair using tow composite. Of interest in Meindertsma's inquiry were the avenues and treatments of the by-products and how these by-products can have an architectural application.

The second focus of composite utilization includes projects that aim to replace synthetic or petrochemical materials with biogenic alternatives. These experiments incorporate flax's mechanical properties into composites to study the material's thermal, structural or acoustic abilities. One example is a test incorporating flax fibres into concrete, exploring if the tensile strength of the fibre can act as rebar replacement (Fernandez 2012). Another composite example uses the flax shives in a fashion similar to hempcrete. Both hemp and flax are bast plants, meaning they have similar material properties and therefore can be interchangeable in this context. Flaxcrete is still under development, but hempcrete utilizes hurds, hemp's hollow woody core, with a binder and bulk-forming methods to create an insulating material (Garikapati et al. 2020; Magwood 2016). Lastly, a research group in France incorporated flax shives in a foaming concrete mix intending to develop a rapid hardening material that provides insulation qualities to 3D printed material (Dubois et al. 2018). Many of these examples use flax materials to substitute existing common architectural materials.

Lastly are recent examples that align themselves with a biogenic future approach. The LivMatS Pavilion is a fibre filament structure using the fibre's high tensile strength, a resin coating and a hollow robotically wound structure to create a self-supporting pavilion (Pérez et al. 2022). The

Chair made from a flax composite (Miendertsma 2010)

Flax Fiber Reinforced Concrete (Fernandez 2012)

Flaxcrete block made by author for The Flaxmobile Farmers Retreat (Recipe from Garikapati et al .2020)

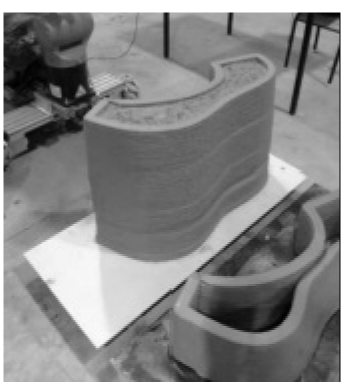


Image of printed concrete containing shives.
(Dubois et al. 2018)

livMatS Pavilion, University of Stuttgart, 2021
(University of Stuttgart, 2021)

BioKnit, HBBE, 2021
(HBBE, 2021)

Biohub pavilion also explored the capabilities of flax fibre as a mycelium growth scaffolding (Scott et al. 2022). The landscape of flax and its by-products highlights current intrigue and testing but is still developing and open for further expansion in multiple areas. This thesis explores flax by-products using additive manufacturing and biomaterial applications to further expand upon this growing body of research.

Digital Fabrication

Digital tools intersecting with architecture are hastening and becoming more prevalent. These tools fall into two categories: Computational Design, and Digital Fabrication. Computational Design refers to a design process that requires digital techniques such as algorithms or generative designs to be realized (Ahlquist and Menges 2011). Digital Fabrication refers to “any manufacturing process controlled by a computer” (Yuan et al. 2017, 13). These manufacturing processes can be either additive or subtractive.

Additive Manufacturing

Additive Manufacturing (AM) is a contemporary form of digital fabrication characterized by creating 3D objects through material deposition in layers. The first 3D printers in the 1980s developed from a need for rapid prototyping. In the early 2000s, a growing community and movement of open-source information expanded accessibility and therefore its use in making, designing and research (Banon and Raspall 2021). This thesis uses paste extrusion, or liquid deposition modelling (LDM), commonly used for clay and concrete printing. This method extrudes a viscous slurry through a nozzle by pressurized or augured systems. The material is deposited onto a print bed through an extrusion nozzle that is moved according to a tool path provided by a sequential set of cartesian X, Y and Z coordinates followed by the speed (F) the nozzle travels between points. This tool path is known as a “G-code”, a programing language that can be generated in Rhino 7’s parametric modelling extension Grasshopper (Cuevas 2020). Once formed, a curing or drying process begins, and the artifact transitions into a solid material. The scale and ability of a printer also offers a range of printing opportunities, from tabletop models, to large-scale commercial units, five-axis robotic arms, and in-situ site gantry systems. Additive manufacturing is a digital fabrication method full of possibilities in combining customized mixes and its ability to print bespoke geometric forms.

Printed additive processes have unique opportunities and limitations, as with all fabrication methods. The most significant limitation is the access to equipment. Small-scale printers are available for purchase and or found in some maker spaces, but easy access to printers with the capability

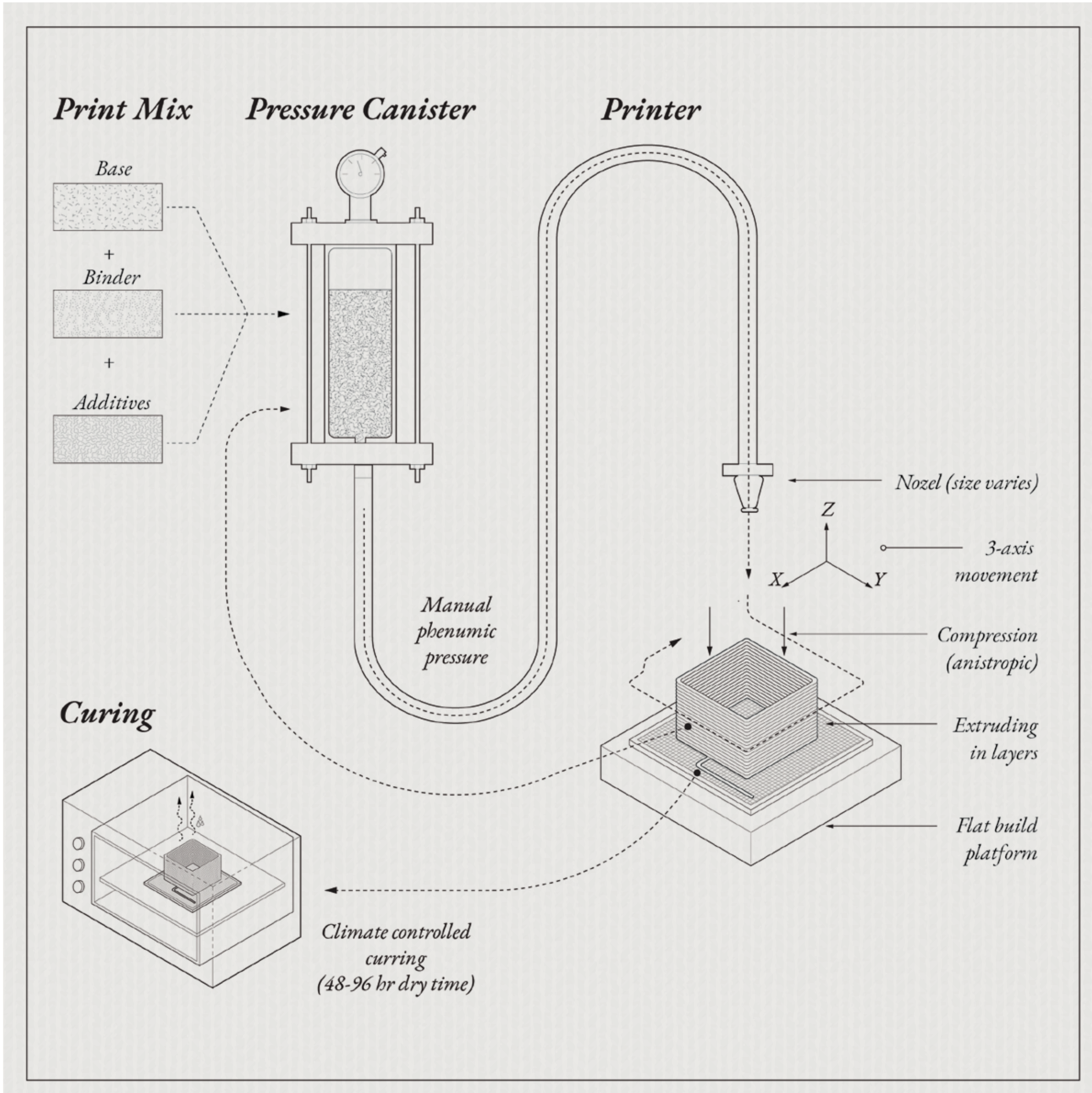


Diagram of Liquid Deposition Modeling

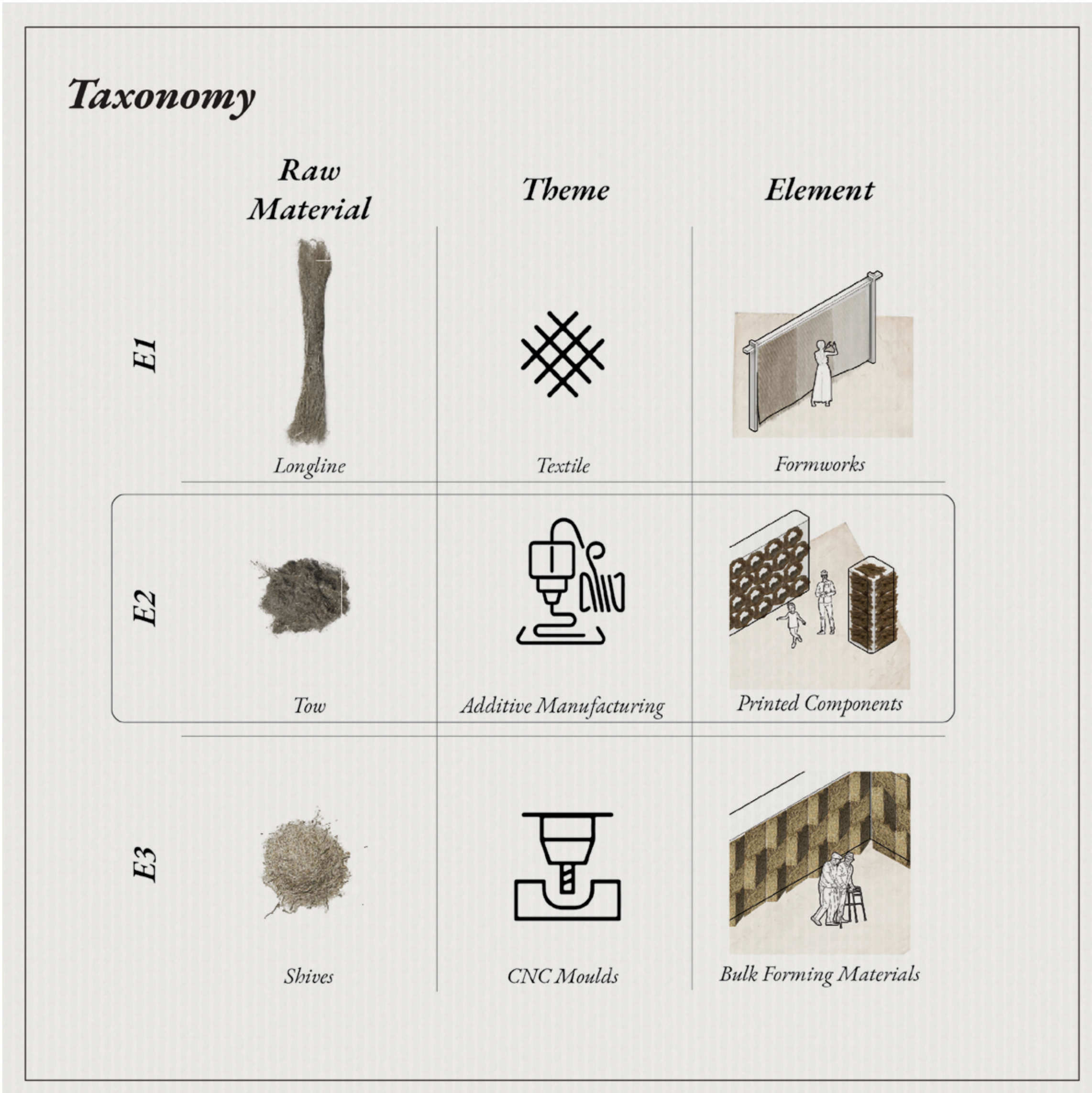
of extruding custom mixes is limited. This thesis used an LDM printer at Dalhousie's Mind Body Environment (MBE) Lab. Other printing limitations include material/equipment cost, size limitations, print time and mechanical performance of the final artifact (Banon and Raspall 2021). Opportunities include geometric freedom, bespoke production and lack of specialized tools as the printer is the only tool needed (Banon and Raspall 2021). Additive manufacturing is also an opportunity for sustainable manufacturing since it can allow for an in-situ fabrication with no waste materials, shipping or surplus. There is also the opportunity for sustainable manufacturing of local and ecological materials. Because of this, additive manufacturing is ideally suited for biomaterial exploration and creation.

Architectural projects using 3D-printed concrete are becoming increasingly common. These projects vary in scale from small hand-held objects to explorations of printing multistory buildings. 3D printed concrete dominates the discourse around 3D printing and has been touted by some as a panacea technology for the housing crisis. However, concrete is well known as a carbon-intensive material. This thesis chooses to align itself with Emerging Objects, resisting techno saviourism or speculation, using additive manufacturing to explore local materials and learn from, and work with, the process of printing (Rael and San Fratello 2018). Emerging Objects is at the forefront of Printing and Architecture with their recent work Casa Covida, a three-room open-air living space 3D printed using adobe (Emerging Objects 2020). Rael and San Frattello have also completed many works using waste materials like coffee grinds, salt, and grape skins to create 3D-printed objects (Rael and San Fratello 2018).

Another project that served as a catalyzing inspiration for this thesis is a continuing research project by the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy that has been researching printing with cellulose-based materials (Rossi et al. 2021). There is also an exploration into using pure biogenic substances like Singapore University's use of cellulose and chitin to print a column or Neri Oxman's Aguahoja project (Dritsas et al. 2020; Mogas-Soldevila et al. 2015). Ultimately, there is a robust and growing body of thought-provoking, transforming, and motivating work is underway in 3D printing research. However, there is a need for an increase in contributions to the discourse of printing with biomaterials.

Taxonomy

The ideas of making, materials, and digital fabrication culminate in a tripartite taxonomy of investigative directions. Toshiko Mori’s projects in immaterial/ultramaterial inspired the structure of the investigative directions. The project “Edge” explored plywood through traditional tailoring techniques to create an architectural element that turned, for example, from a floor to a wall (Mori 2002). An outline of this structure first determines a material, then explores it through a digital fabrication theme, therefore creating an architectural element. The first proposed experiment, titled E1, sought to use the longline fibres, or drafted and spun strings, to explore the material through a theme of textiles that would create a formwork. The second experiment, titled E2, sought to use the short tow fibres that are a by-product of processing and explore them through 3D printing to create architectural components that can aggregate into an architectural element. The third experiment, titled E3, sought to use the shives and explore bulk forming methods through CNC moulds to create block architectural components that can build into an architectural space. Simple proof of concept experiments were completed, and as this thesis progressed it became evident that focusing on one of these methods of investigation was necessary, and 3D printing was chosen to be further developed in this thesis.



Taxonomy diagram of thesis experiments (Theme images from The Noun Project 2022 and raw material photos from Miendertsma 2010)

Thesis Method

The working method of this thesis contains fixed and variable elements. The fixed elements keep the method applicable to biogenic material investigations, and variable elements test this method in different local contexts. The method consists of scales nested within one another, with most investigations happening at the material scale. The fixed element at the global scale is Biogenic Materials. In

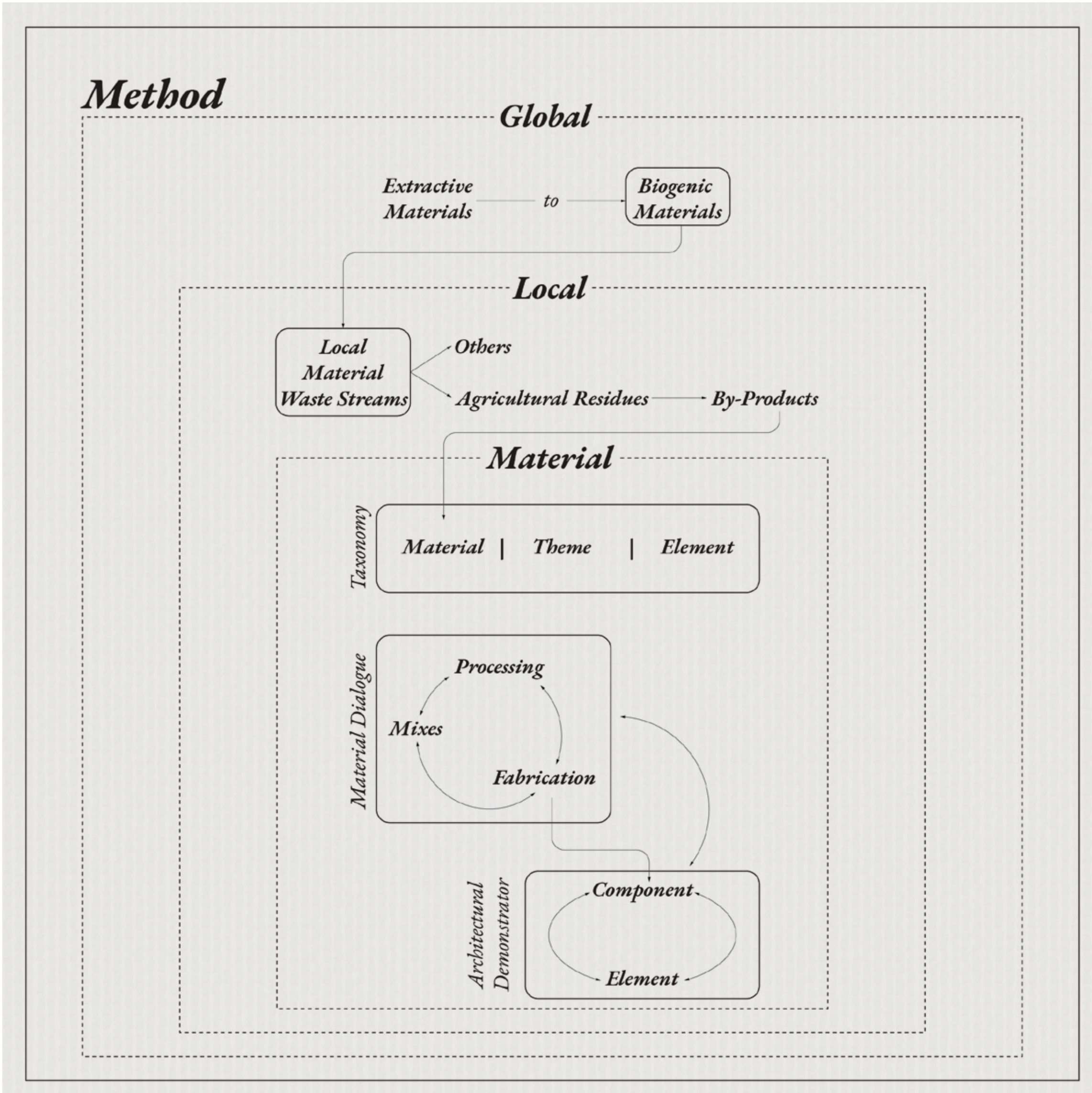


Diagram of the thesis working method. The three scales Global, Local and Material are nested within each other. Within each scale fixed elements are boldly outlined and variable elements are filled in.

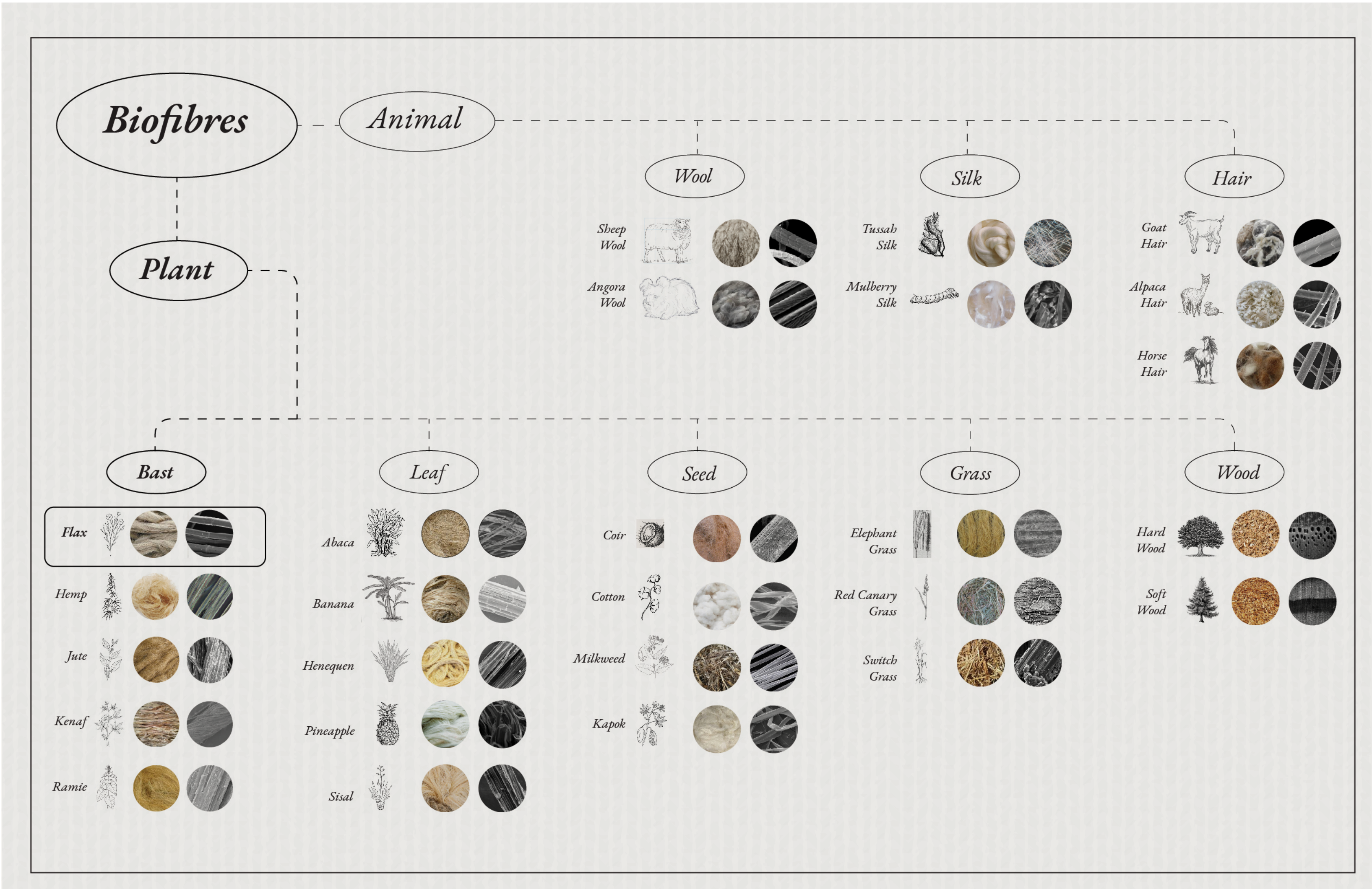
this thesis, they are reacting to the extractive implications of architectural materials. At the local scale, the fixed element is local material waste streams. This thesis exploration utilizes by-products of agricultural processes. The last scale is material and involves material experimentation. The experiment parameters use the taxonomy of material, theme and element. To create an element, the material exploration through two processes a material dialogue and an architectural demonstrator. The material dialogue engages with the material to develop a protocol for processing the by-product, testing the biomaterial mix, troubleshooting, and tailoring the material for the chosen fabrication process. With an established working material, a component aggregates to create an architectural demonstrator.

Chapter 3: Background

Biofibres, or fibres of biological origins, are naturally occurring cellulose materials that grow with unique properties that develop as a part of their specific growing conditions. There are two types of biological natural fibres: protein fibres and plant fibres. Protein fibres are from animal sources, such as hairs or silks, and plant fibres are composed of cellulose. Cellulose is a crystalline molecule that is a significant component of plant cell walls (Fry 2003) and the most abundant biopolymer on earth (Ibid.). Plants clean and pull carbon from our atmosphere and sequester them, turning carbon into something useful, and at their end-of-life, biodegrade, breaking down to be built back up again in a new form of useful carbon (King 2017). The availability of these sources is annual for agricultural plants. Architecture has traditionally used biofibres and their by-products. Fibrous plants were cultivated for the fibres used for cords, twine, string and woven fabrics. These became textiles, clothing, tents and enclosures. In building, these materials are for thatching, bulk-forming material and use in composites.

Flax

The Latin name for flax is *Linum usitatissimum* and translates to “the most useful” (Kolodziejczyk and Fedec 1995). Flax plants have long, slender stalks and blue-purple or white flowers, depending on the variety. The fibres produced are long, lustrous, flexible, durable blonde strands. There are two significant cultivars of flax, one grown to emphasize seed production for linseed or flaxseed oil, and another to emphasize fibres. Seed varieties are shorter than their fibre plants. The Canadian prairies are a significant global



Biofibre diagram broken into plant and animal based sources.

Longline Flax Photo
(Mienderstma 2020)

producer of flax seeds (FAOSTAT 2021). While the by-products of this cultivar are not explored in this thesis, there is an opportunity for future study in this area. Historical documents show that the waste material was used to make cigarette and fine bond papers (Canadian Department of Agriculture 1968). Currently, the shives are of interest in Canada as a biofuel, however, transport distance is a barrier to viability (Flax Council of Canada n.d.). The second type, which is the focus of this thesis, is fibre flax, which produces the fibre for linen textiles.

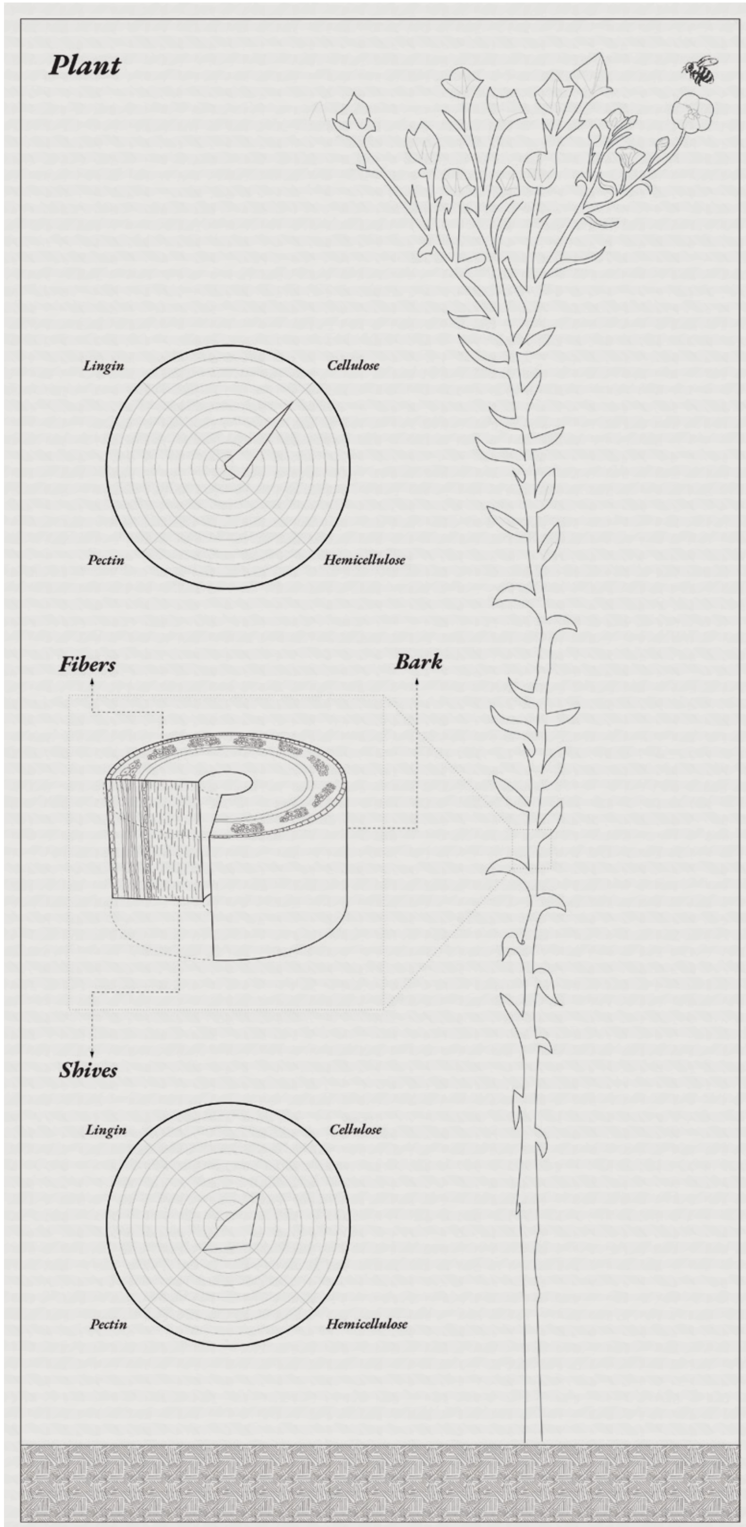
Flax has a simple structure, from exterior to interior the composition of the plant is in three parts: the outer bark, the inner fibre bundles, and the hollow woody core. Flax has only primary fibres, making extracting the fibres from the core a straight forward process. The fibres run longitudinally from the root to the tip and have the highest cellulose content of the plant (Van Dam and Gorshkova 2003). Cellulose gives the fibres their strong, flexible hydrophilic nature (Yan et al. 2014). The fibres bundle in clusters of 10 to 40 fibres, and each elementary fibre has four layers with a hollow lumen at the centre (Ibid.). The xylem or shives is the hollow woody core of the plant with a lower cellulose content and comprised of varying hollow chambers in height, width and length (Nuez et al. 2021). The fibres are of interest because of their high strength-to-weight ratio, which is stronger than other plant fibres (Yan et al. 2014). However, their hydrophilic nature provides difficulties in working with the material because of their responsiveness to environmental humidity factors. Shives are of interest because of their similarities to materials like straw and hemp hurds, although the research on flax shives is limited and warrants further exploration.

History

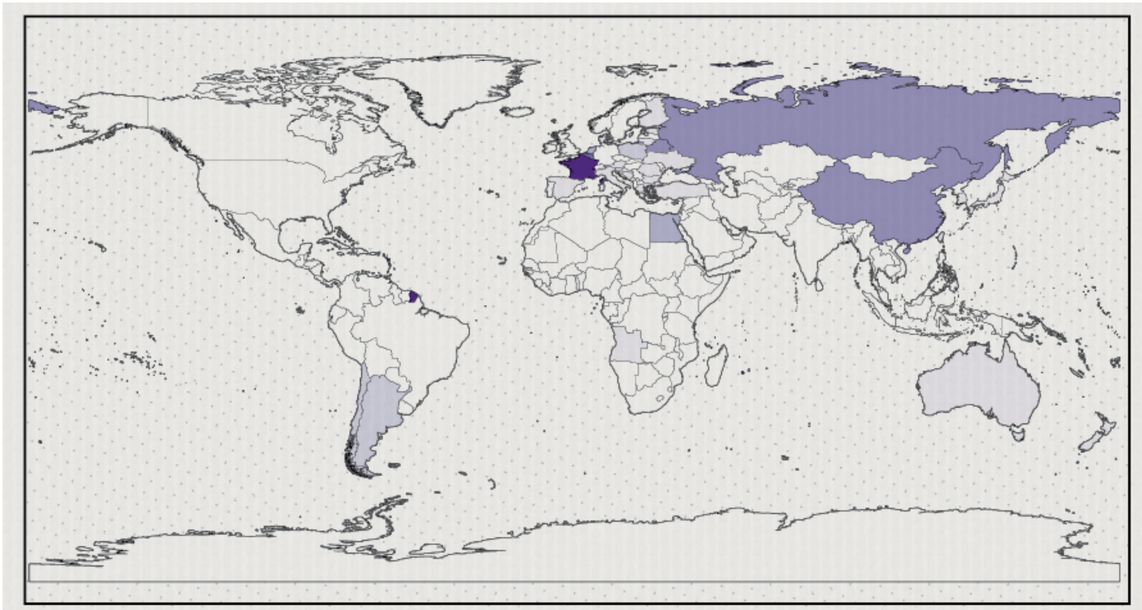
Flax has a long-intertwined history with human development, movement, industry, and cultivation. Found samples of linen fabrics date back 30,000 years (Yan et al. 2014). Wild flax originates in the fertile crescent and spread across Egypt and Europe. In the seventeenth century, French colonists brought flax to North America (Vaisey-Genser and Morris 2003). In the nineteenth century, the industrial revolution and the rise of the cotton industry brought about the collapse of the linen industry. In the 1980s, fibre flax production regained interest due to consumer interest (Ibid.). Contemporary significant producers of fiber flax include Belgium, France and Egypt (FAOSTAT 2021). Today, consumers are more conscious of the materials in their clothing, and flax is growing in interest, especially at the local scale.

Flax in Nova Scotia

Nova Scotia has a long history with fibre flax and two projects growing the contemporary industry. Flax was introduced to Nova Scotia via settler colonialism at the Port Royal Settlement. Following the global trend, flax production in Nova Scotia ceased and has grown and developed in the last few decades because of an interest in locally grown textiles and crafts. The first is TapRoot Fibre lab, a small batch linen producer (TapRoot Fibre 2023). They have developed mechanized facilities for processing and spinning Flax. The second is The Flaxmobile Project, a three-phase research project that trains committed farmers in Flax growing and processing (The Flaxmobile Project 2023). Both these projects have an emphasis on the local economy and sustainability.



Drawing and section of flax plant section (Composition information from Van Dam and Gorshkova 2003).



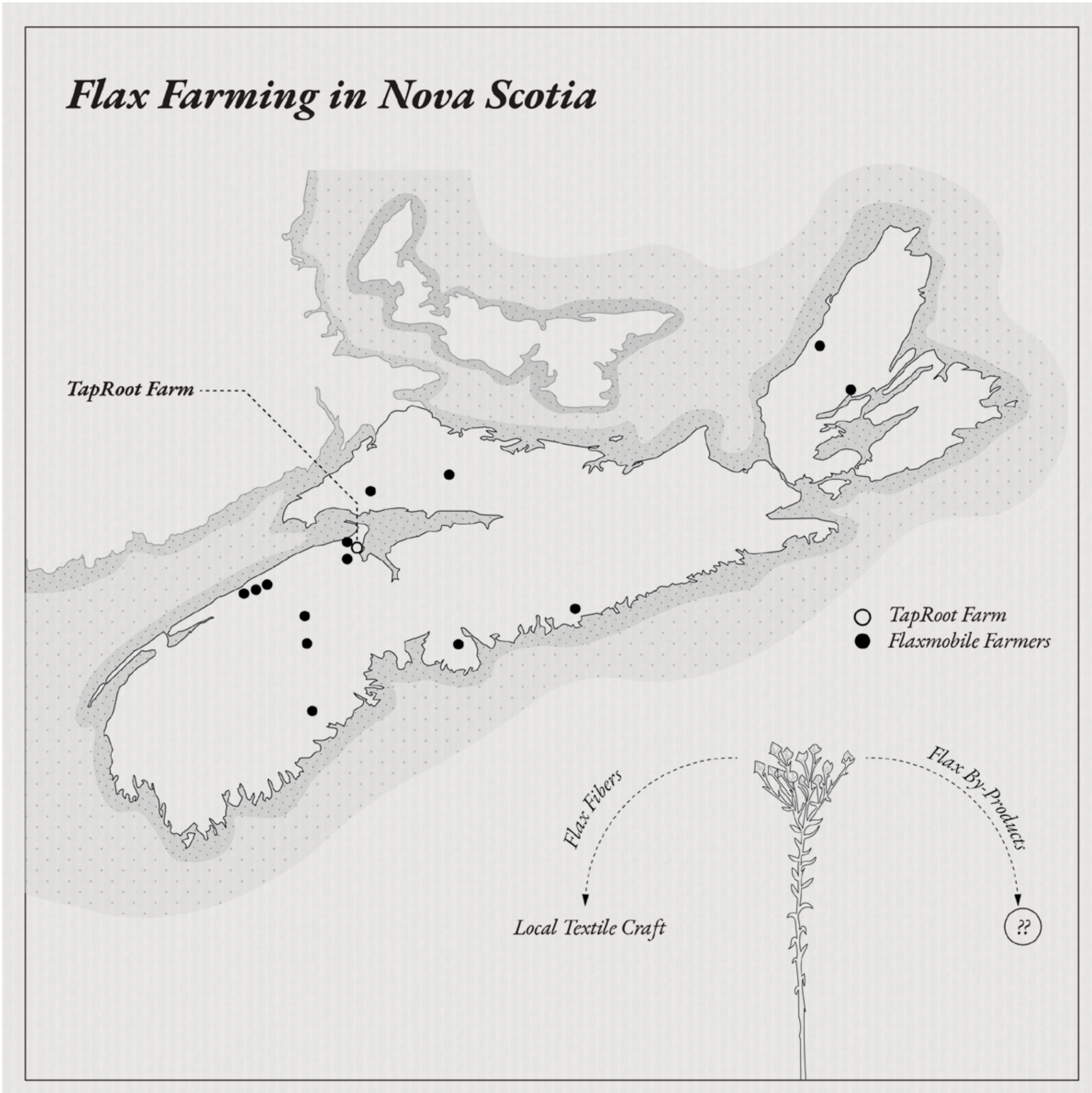
Map showing 2021 global processed fiber flax production in tonnes. Top 5 countries are France, Belgium, Belarus China and Russia. Map created using arcGIS and information is from the Food and Agriculture Organization of the United Nations (FAOSTAT 2023)

Personal Experience

In late January 2023, I visited the TapRoot processing facility. Using some gifted retted flax, I unsuccessfully tried to process the material. I also assisted with processing fibres from The Flaxmobile 2022 participants and gathered the tow by-products for experimentation. In March 2023, I attended the Flaxmobile Farmers Retreat and assisted with a Flaxcrete workshop. It was a fantastic experience to converse and engage with farmers growing this material. I was intrigued by conversations and excitement about using these materials in temporary farm structures and buildings.

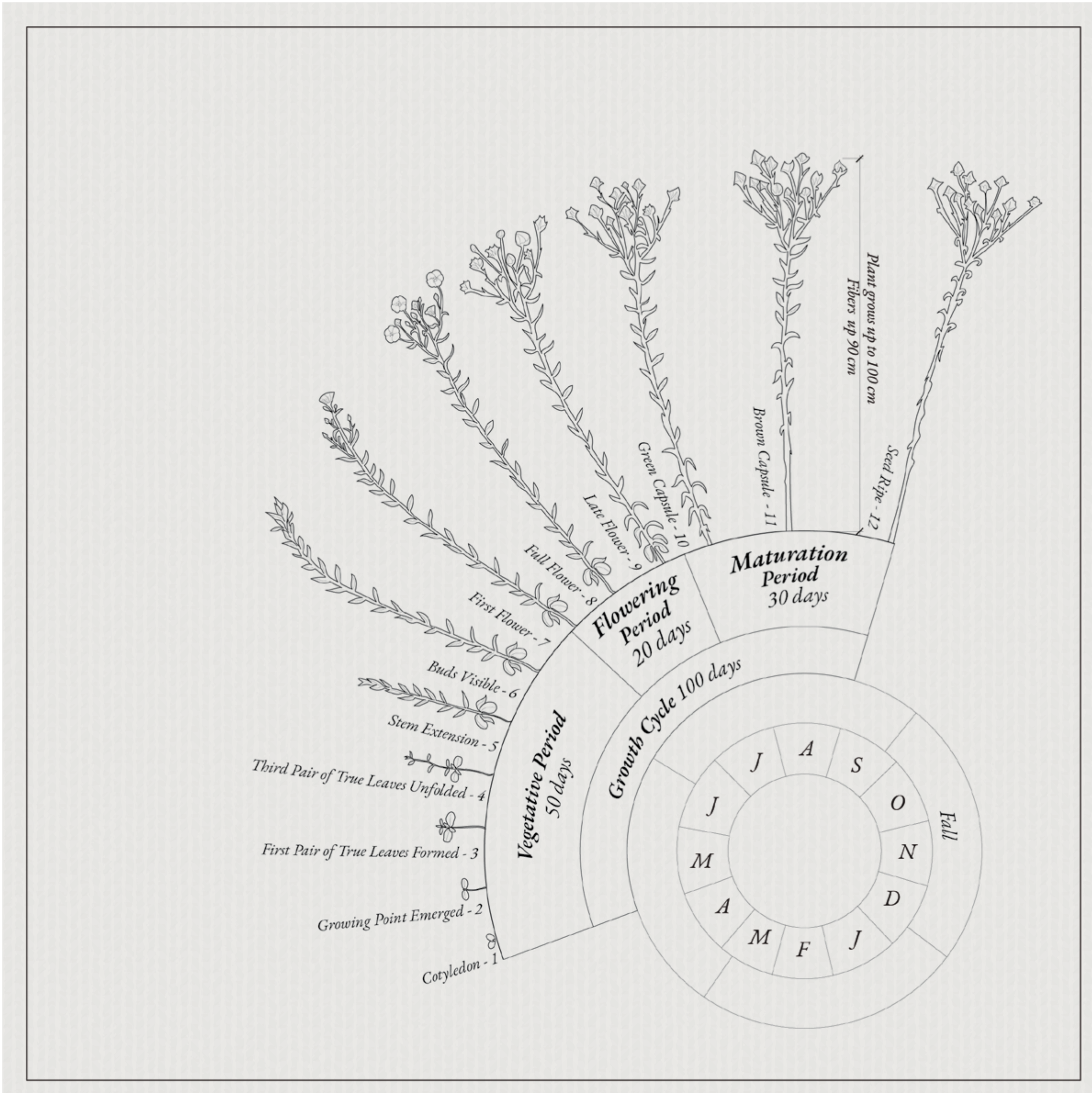
Production

Flax is an annual crop, making it a rapidly renewable resource, with the flax growing cycle occurring between 90-125 days. This cycle involves three growing periods with 12 distinct growth stages (Flax Council of Canada n.d.). In Nova Scotia, the growing cycle for flax is 100 days, meaning the plant is well suited to the climate. The plant requires an average of 6mm of water per day, and additional irrigation



Map showing flax farming in Nova Scotia (The Flaxmobile 2023)

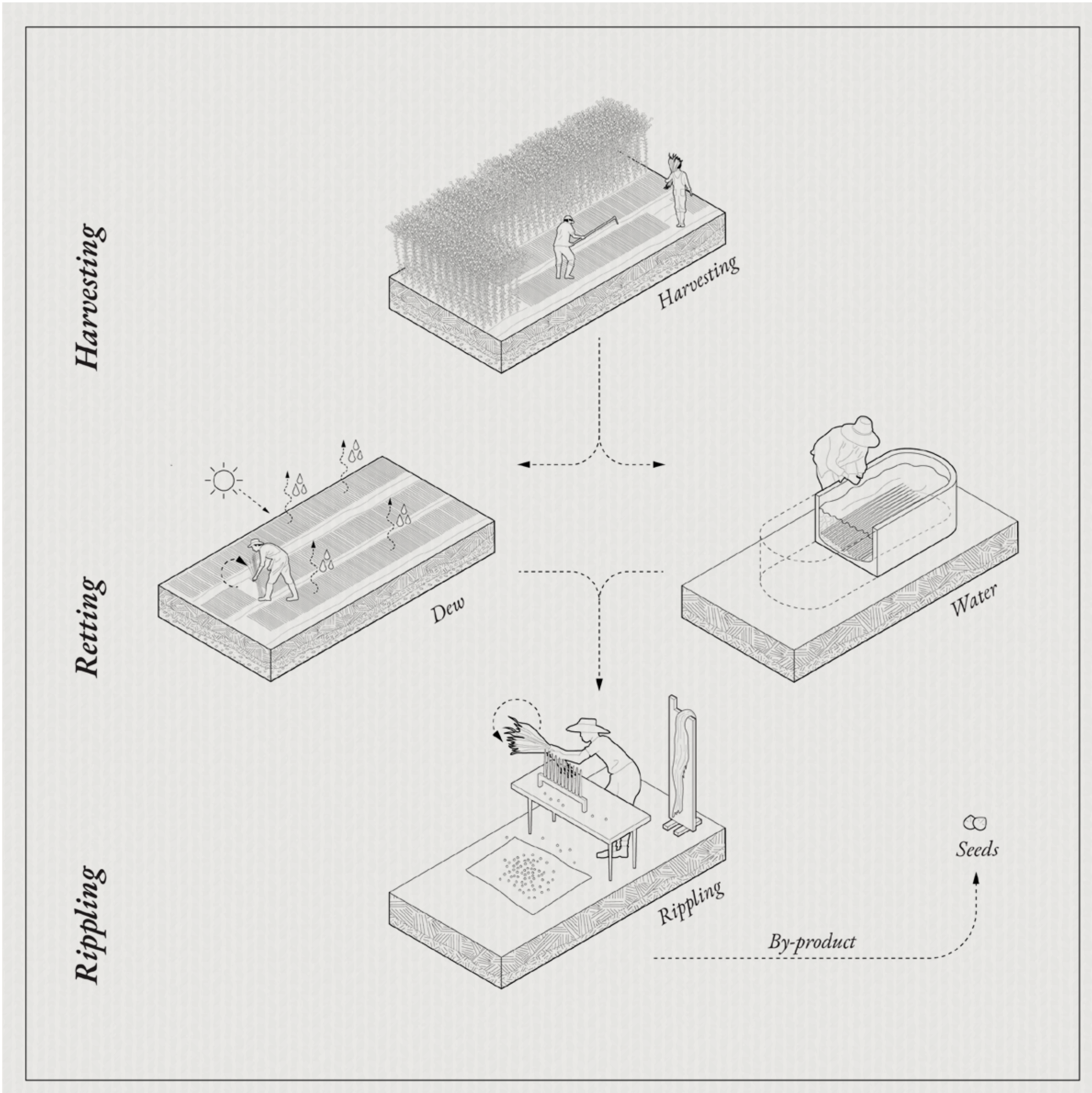
is not required in most cases. Also, the plant requires little to no fertilizer and can be used in crop rotation to replenish soils by breaking up disease and insect populations (Ibid.), further adding to the plant's sustainability. There is also evidence that flax has a good potential for soil remediation, drawing toxins out of the ground (Griga et al. 2013). In Nova Scotia, fibre flax is usually planted at the beginning of May and harvested in late August, pending the growing year.



Growing stages from the (Data from Flax Council of Canada n.d).

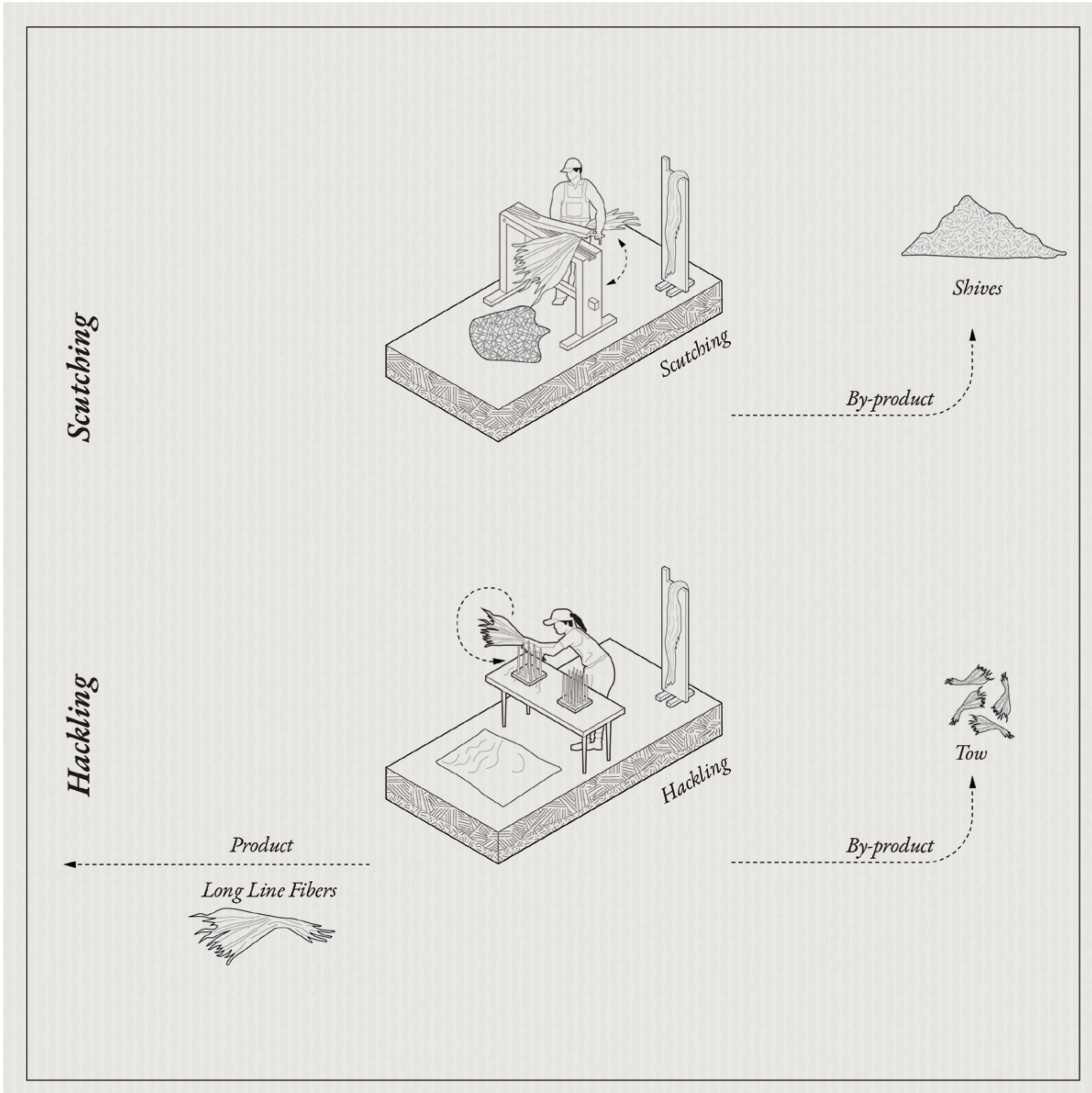
Harvesting

Once the plants have reached the maturation stage, they are ready to be harvested. They are pulled out by their roots or cut close to the ground to preserve the fibre length. The plant stalks are laid in the field or taken to vat for the following retting process. During retting, the outer bark degrades away via moisture, and the inner part dries. Dew retting occurs in the field where the stalks are periodically flipped, and the natural precipitation and humidity degrade the outer



Harvesting diagram showing process and by-products

bark over two weeks. Vat or water retting submerges the stalks in water, accelerating the process. Next, rippling extracts the seeds from plants through a manual combing process. Rippling produces two by-products: chaff, which is the material around the seed pod, and flax seeds. These materials are not explored in this thesis. Rippled and retted flax stalks are the material feedstock processed for fibre extraction.



Processing diagram showing products and by-products

Processing

The main objective of processing is to extract the longline fibres, which are the high-value product of the plant. The by-products of these processes are fibres that are too short for textile production, which are lint or tow, and the shives that are the hollow wooden core of the plant. The first process is called scutching, a mechanical process that breaks the shives into smaller segments that fall away, leaving the full-length fibres behind. In the industrial process, the materials are run through successive turbines breaking the inner core. In small-scale production, the retted fibres are beaten in an interlocking wooden hand brake to break up the core. This process produces the shive by-product while some pieces remain on the fibres. The following hackling process combs the fibres with closely spaced metal combs pulling away the shorter fibres and remaining pieces of shives. Next, the long line fibres are combed repeatedly and pressed until only the high-quality fibres remain. These longline fibres are then further processed to create textile products. The shive by-products that result from this process are utilized for this thesis experiment.

Chapter 4: Material Dialogue

Shives

The three sections in this chapter involve different levels of inquiry and operate in feedback loops, informing each other with each printing test. The initial material investigation of printing with the by-product tow was not feasible with the printer available, and an investigation into printing with the shives by-products began.

Material Processing

Cleaned shives

Lint

Material processing is the first level of the material dialogue. It consists of any treatment to the agricultural by-product needed to make this material useable for experimentation. LDM requires a homogeneous mixture that can maintain its stability through extrusion, meaning the base material needs to be fine particles, or the binder must be strong enough to suspend the base material. Since the raw shives are rigid tubular elements that vary in length, the opposite of homogenous, a protocol was needed to prepare the by-product for printing. The protocol workflow is; mechanical separation through sifting, washing, heat sterilization, blending, then fine sifting. The development of this protocol started as an exploratory process. It changed throughout this thesis with the development of a tacit understanding of the material and availability of a Vitamix high-power blender.

Protocol Summary

Flax powder

During the initial mechanical separation process, removing miscellaneous items, including garbage and large under-retted fibres, is vital as these items tangle and block the blender blade. Sifting using a curved metal wire mesh was chosen because it supports a visual inspection, and the movement clumps the unwanted fibres together, making

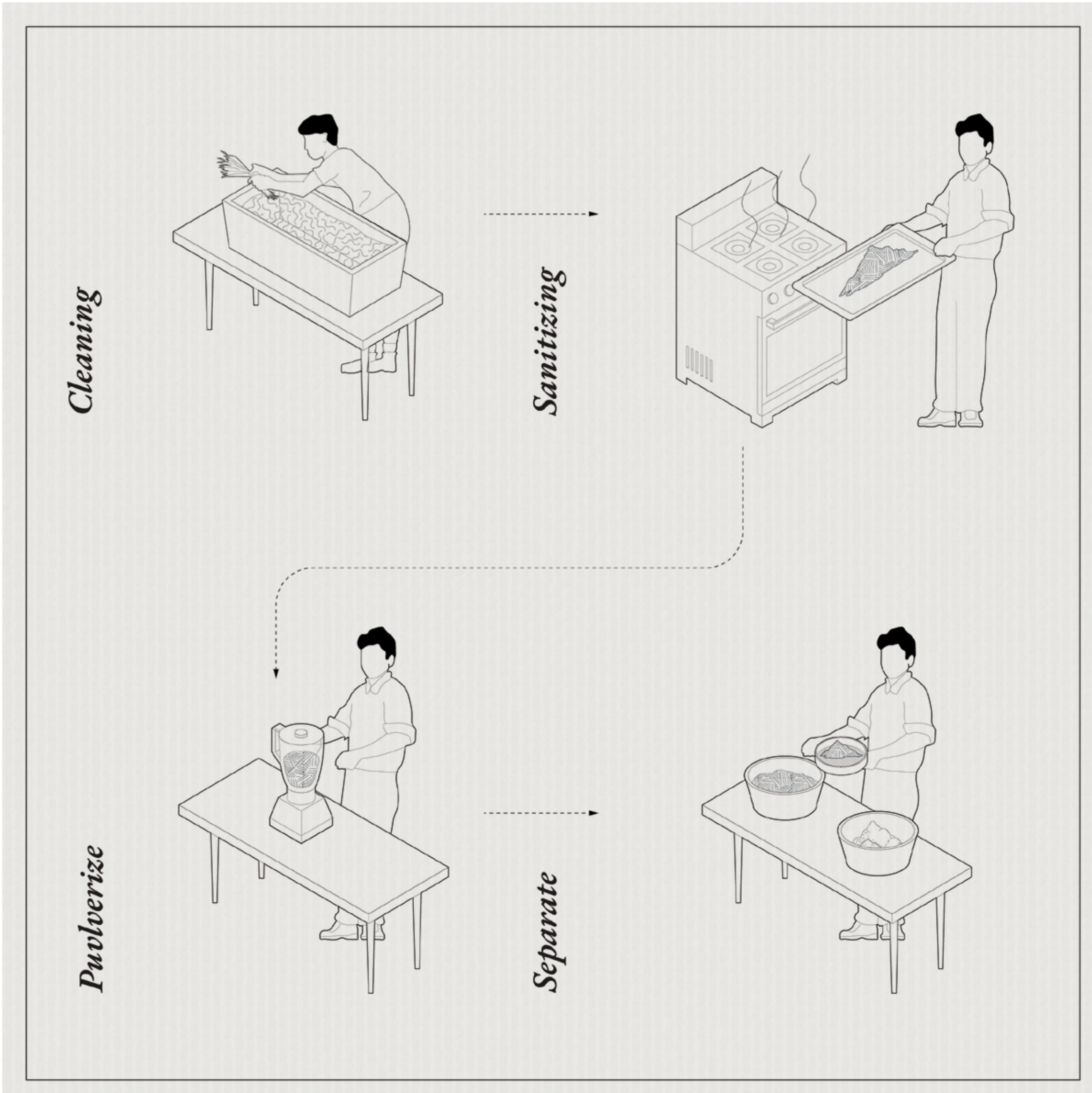


Diagram of cleaning protocol

them easier to remove. The washing process cleaned the shives by soaking them in water. The shives float while dirt, seeds and debris typically sink. After a few rinses, the shives are pressed to remove excess moisture and thinly laid on lined trays. These trays are placed in a conventional oven set to 100 degrees Celsius for 1.5 hours. Heat sanitizing was chosen to sanitize the material because it dried the shives quickly. Lastly, the sanitized shives are gradually blended into a fine powder. This powder goes through a final mechanical separation cycle with a finer mesh colander that removes the lint and any larger pieces of shive that create blockages in the printer.

Mix

Xanthum gum

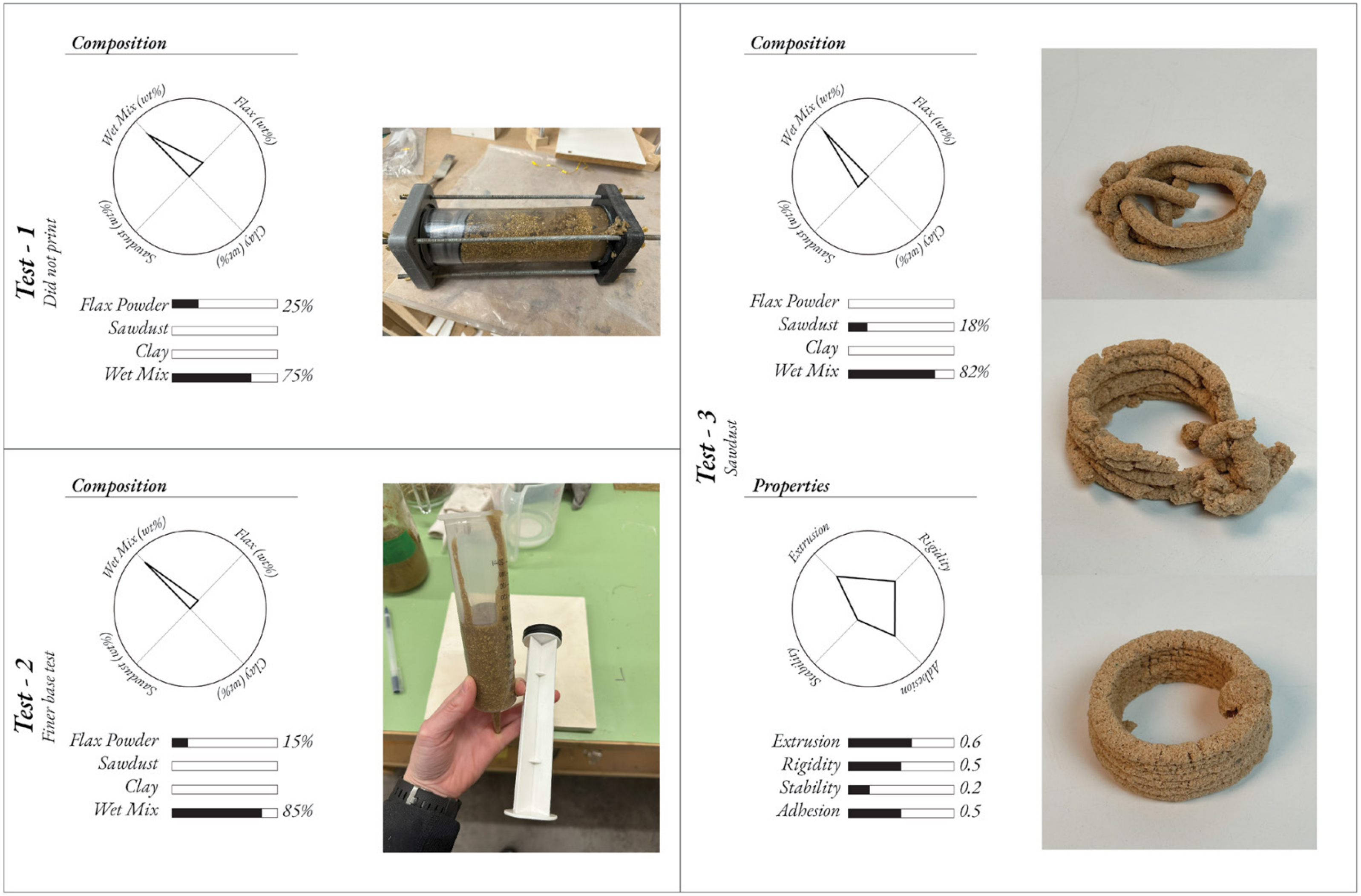
Glycerol

This mix started with an open-source recipe for a xanthan gum and cellulose floc slurry intended for 3D printing from a research group at CITA (Rossi et al. 2021). This mix provided a starting point, and adjustments were made throughout the printing process to get the desired result. A printing mix comprises two main components, a base and a binder, additives can be included to create a desired effect. The intended base is the flax powder derived from the flax by-products. The base is the most visible part of the mix and contributes to the mechanical properties of the final print. The base can also be considered as the dry ingredient of the mix. The binder for this experiment is the adhesive and viscous part of the mix. The binder homogenously suspends the base for extrusion and adheres the base together when dry.

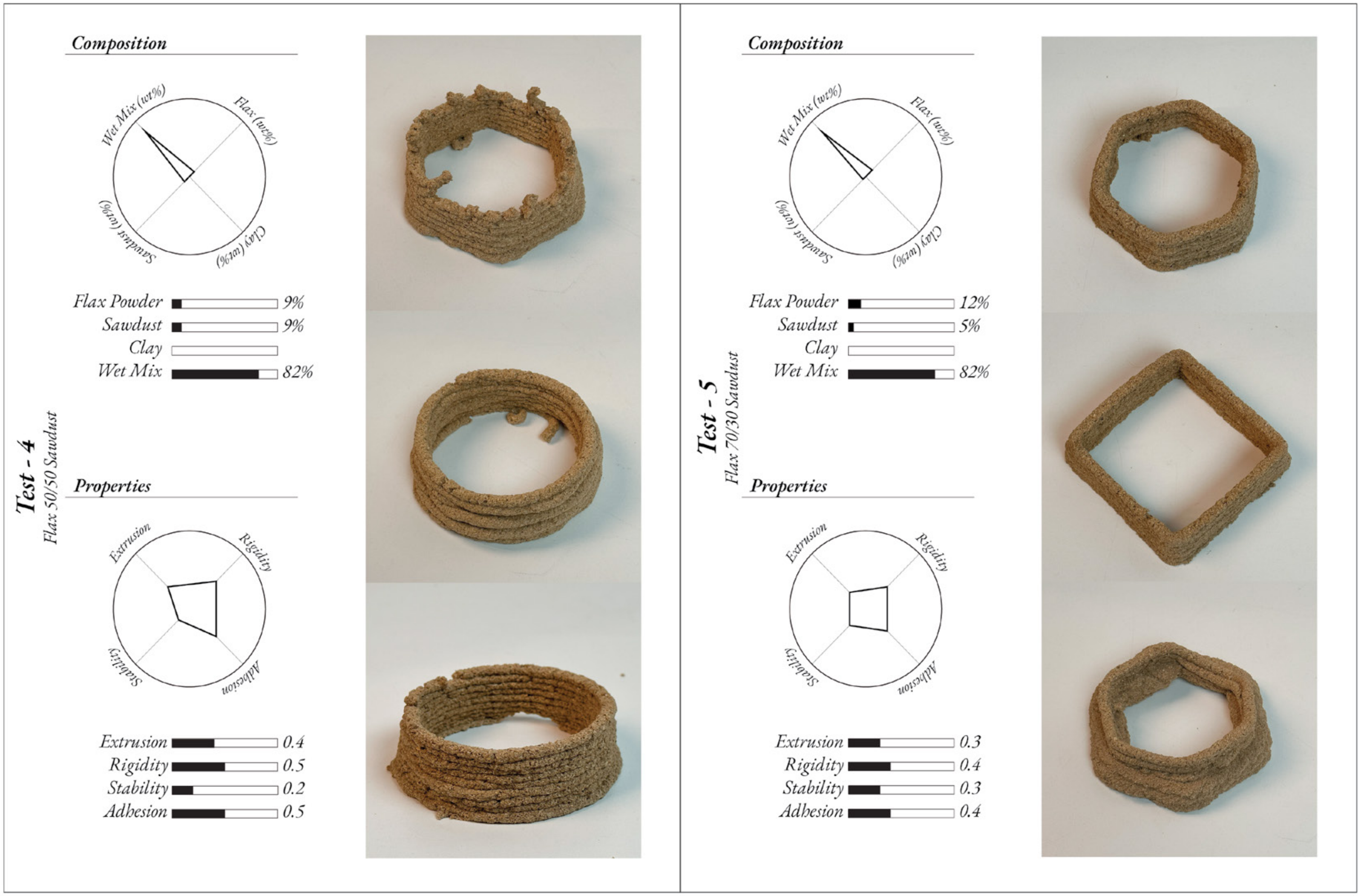
Mix Design

Water

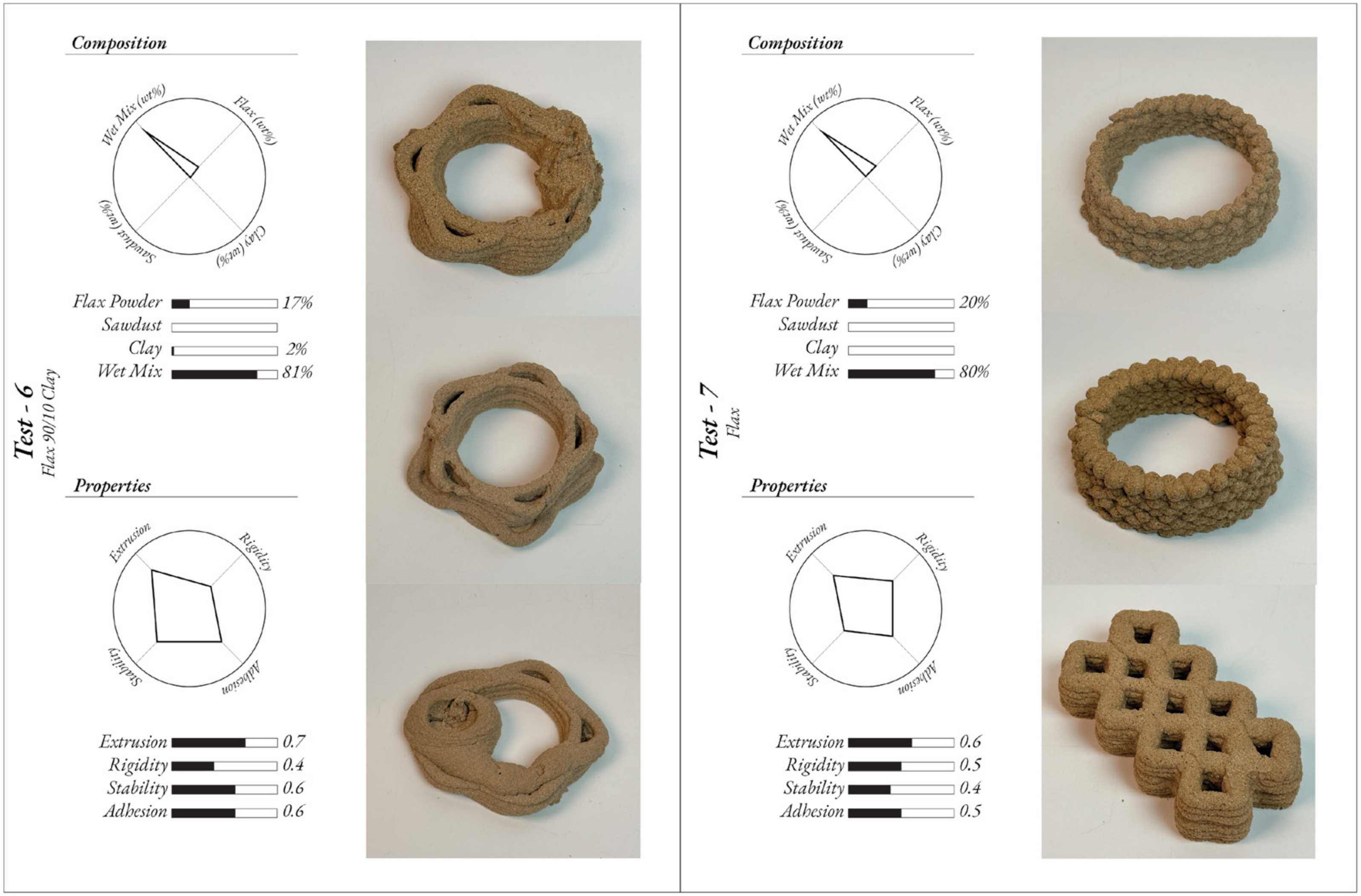
The binder used in this thesis is a mixture of xanthan gum, glycerol and water. An alternative binder, sodium alginate, was tested but showed high levels of shrinkage and deformation and further investigation ceased. The main ingredients of the binder did not change, but the quantities did adjust throughout the printing process. Xanthum gum is a manufactured emulsifier and thickening agent typically used in food products (Materiom, 2022). Glycerol is a thick viscous liquid that aids in stabilizing food products (Ibid.).In working with the mix it was discovered that increased quantities of xanthan gum contributed to the rigidity of the



Print logs of tests 1-3.



Print logs of tests 4 and 5.



Print logs of tests 6 and 7.

Image of the effect of an air bubble on a print

material, and increased an undesirable adhesiveness. Glycerol added a stabilizing and consistency element to this adhesiveness but would undermine the mix in too high of a quantity. Throughout this process, it was found that a velvety and pliable mix was preferred.

Extrusion

The LDM printer this thesis used is controlled by manual pressure. This influenced two critical limitations in the final prints. The first is the inability to start and stop, meaning the prints must be designed to work with a continuous tool path on each layer. To accommodate this, a “skirt” and a “tail” were added to each print path. Skirts are standard practice in extrusion printing and allow for pressure adjustments before the final print. The “tail” was a vertical line that started at the last point of the print path and travelled directly up. This allowed for the print bead to be cut and not interfere with the final print. Second, great attention and manipulation of the

Surviving epistemic artifacts of printing process.

pressure is needed during the print to ensure a consistent print bead. The G-code speed and manual pressure were frequently adjusted to achieve consistency. Another factor influencing the print bead is the nozzle size of the printer head. The minimum nozzle size for printing was 5 mm, as extrusion was not possible with smaller sizes.

Extrusion Parameters

Throughout this process, a set of printing parameters developed. These are related to the final print's size, aesthetic and performance. Size restrictions were set at a maximum diameter of 6" and a maximum height of 10-12 layers. Exceeding the layer height resulted in the materials self-weight compressing the bottom layers or the entire print slumping. The height between layers was set at 3mm as it was found to have the preferable layer adhesion. Initial prints used a single bead path, but as the thesis progressed, these prints were found to be flimsy and needed better adhesion at connecting points within the tool path. A larger nozzle head would create more overlap in the printer path, helping this adhesion problem by creating a more significant overlap but decreased resolution in the final print and required adjustments to the mix. It was decided to increase the print wall thickness by the printer path instead.

Printer Modifications

Throughout this process, modifications to the print setup were required to achieve successful prints and respond to printing problems. Printer plates are required to provide a surface for the print to adhere too. The first plates fabricated were plaster. Plaster plates are commonly used for clay printing, but it was quickly discovered that biomaterial mixes firmly adhered to the plates making them difficult or unable to be removed. These plates needed to be better suited for the drying kiln. This led to the fabrication of custom perforated plates, designed to be quickly fabricated, allowing adequate airflow drying and supporting the print’s weight. Another modification constructed a jig that maintained the canister vertically while under pressure. This was key to maintaining consistent pressure on the material in the canister. The vertical orientation worked with gravity preventing material slumpage and air bubbles. Before this modification, the material would unexpectedly slump in the canister sending an air pocket through the extrusion tube, resulting in a catastrophic effect on a print.

Mix Properties

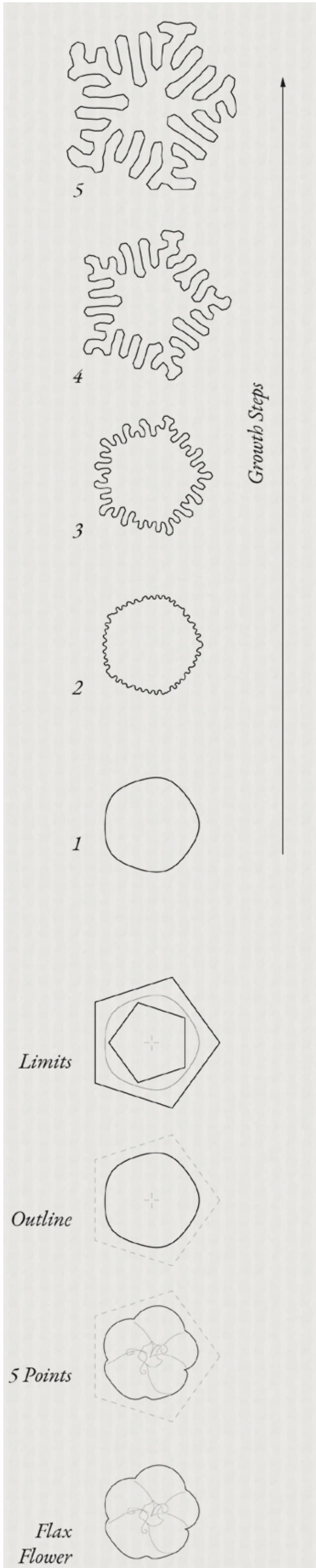
The mix properties sought after for successful printing material are as follows:

- Extrudability: A mix that can extrude with minimal complications was key
- Dry Time: Pending the environmental conditions, prints took between 2-6 days to dry. The use of a climactically controlled environment speeds up the drying process minimizing deformations
- Shrinkage: The materials shrink during the curing process these materials typically shrink most in the Z axis and on average 5- 15% in x and y directions
- Stability: Refers to the stability of the bead of printed material
- Adhesion: Refers to the adhesion between print beads and layers

Alternative mix with lint

Alternative Base Material

The initial taxonomy sought to print with the tow fibres. However, the printer could not accommodate this because the fibres clump and tangle with the pressurized system. During the Farmer's Retreat, a conversation with the papermaker of Flying Finch Studio inspired a second attempt to print with this material. In paper making, flax fibres are boiled in a soda ash solution to clean the fibres, then run through a Hollander beater that continuously cuts the fibres into finer and finer pieces. Following this method, the lint generated from the flax powder production was boiled in 1-part soda ash and 4-part water solution for two hours. The lint was then rinsed and pulsed in the blender. The blender did not produce the same refined tiny fibres observed from the paper-making process and had clumping issues. The material was pressed similarly to paper making and formed into an approximate shape of a print. The resulting material had no binder and was surprisingly dense and rigid. This material still shows excellent promise for printing, perhaps with a different machine or delivery system.



Column design diagram

Chapter 5: Components and Elements

In developing the components to print, a modest goal of self-supporting architectural elements guided the explorations. The architectural elements chosen were a column, a wall and an enclosure. With each test, the intention was to develop a printable language that could be translated and scaled up into an architectural element. Printed components rely on mass and compression for their bearing capacity, which was an underlying design consideration throughout these processes. Each element design is guided by an intention to develop the printing language. The experiment is summarized and concludes by speculating on architectural uses for scaling up.

Column

Intention

This test is intended to test an algorithmically generated design. The intended components are designed for vertical stacking.

Summary

In researching the discourse of printed biomaterials, growth diffusion algorithms were commonly used. This algorithm operates on the principles of a single line that “grows” within the confines of its collision parameters. For example, the line generated by the algorithm becomes the centre line of the tool path, and the collision parameters can represent the width of the nozzle. These lines grow within a 2D plane and do not intersect with themselves. These factors made them ideal for working within the printer design parameters.

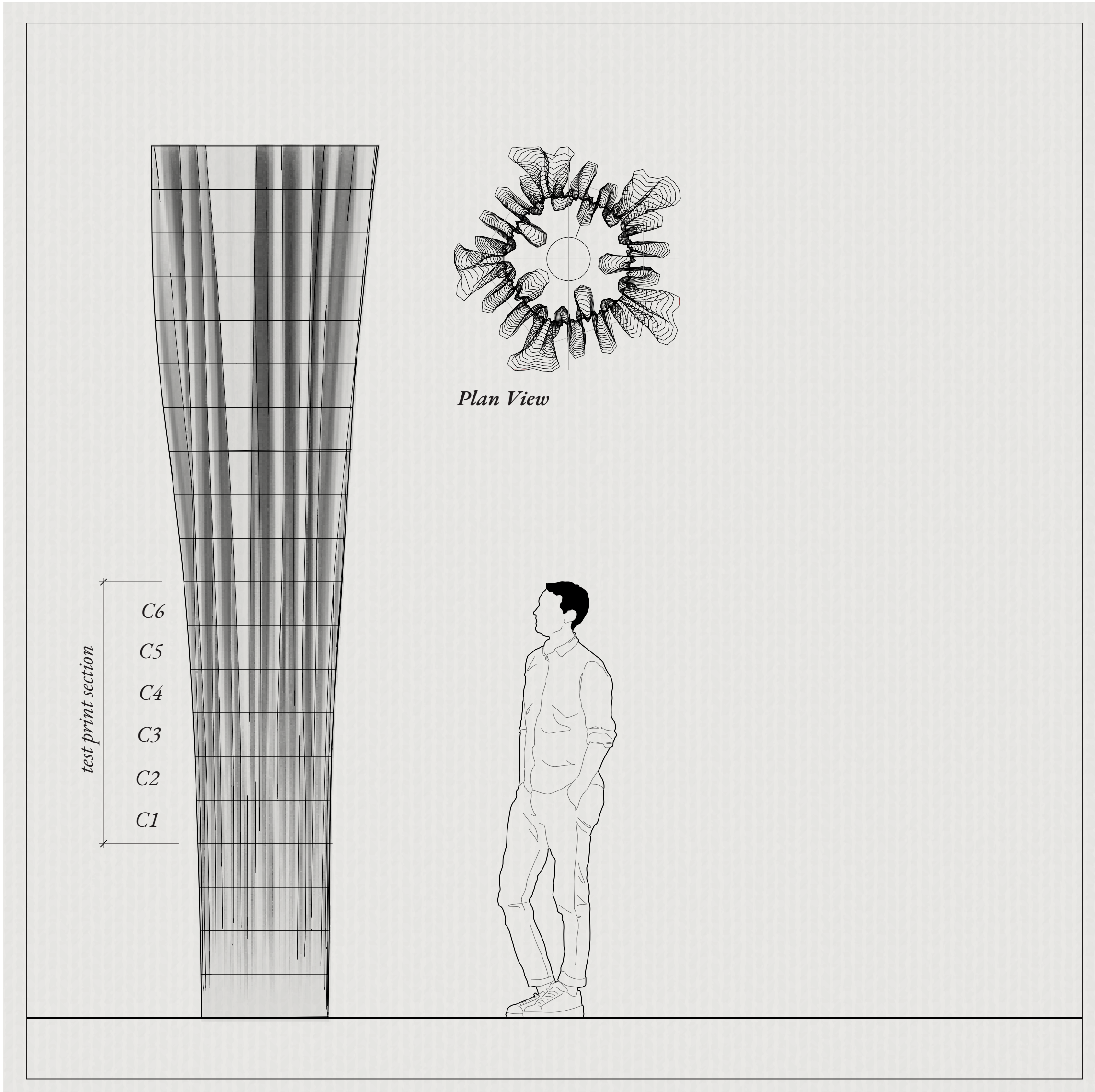
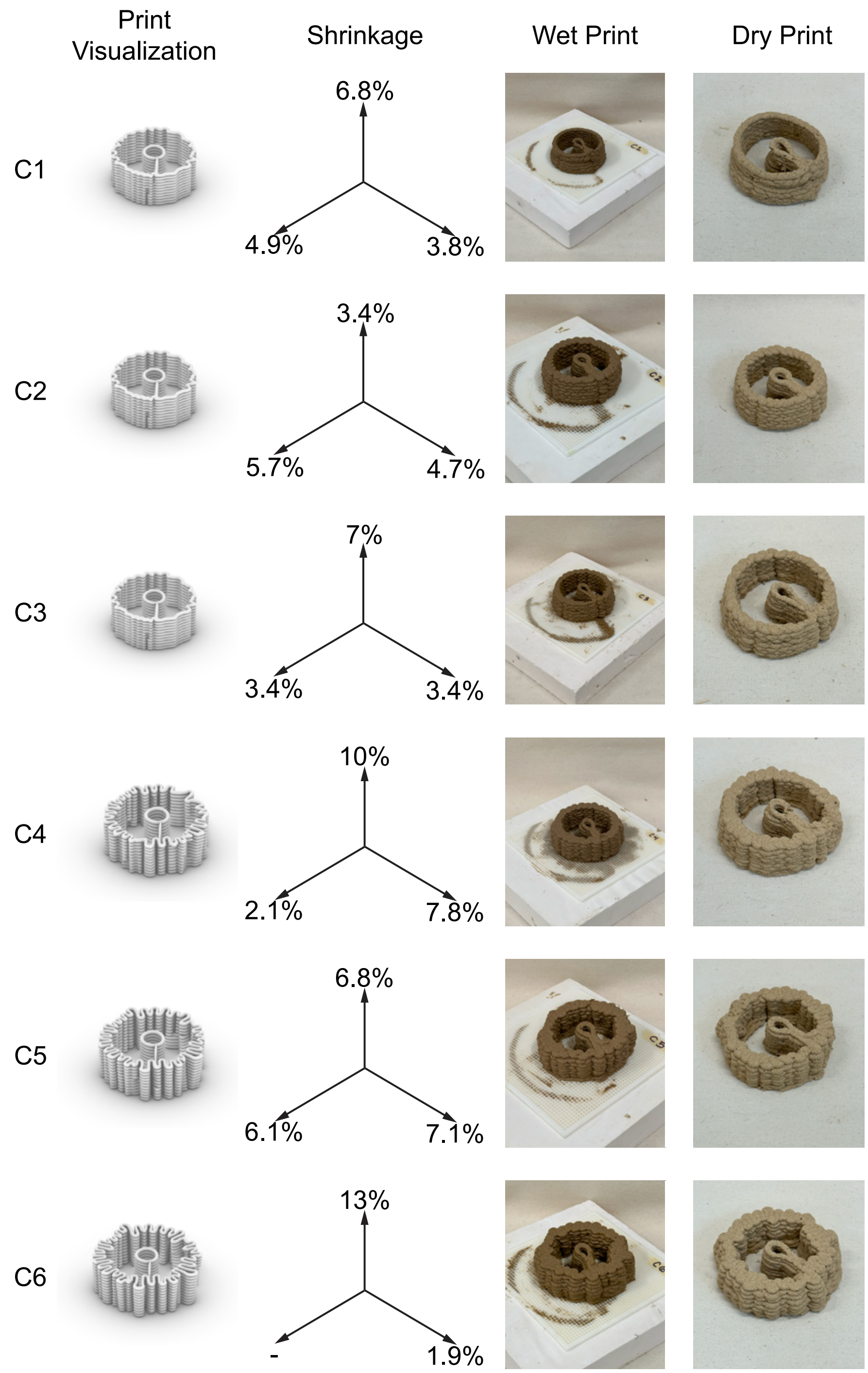


Diagram of column design showing section of printed sample

The nature of these lines is organic and can only be generated and tested in a digital realm. At first glance, these algorithms are complex and devoid of logic but represent a system of growth and iteration like fractals.

The logic behind this design began with an abstraction of a flax flower. First, parameters ensure the algorithm did not grow beyond the printable parameters. The base of the design has five rounded points abstracted from the flower of



Column print analysis

Images of the stacked column prints

Print form section higher on the column showing the intended external surface variance

the flax plant and is the base geometry for the column. The geometry at the top represents the maximum lengthening of the line within the set parameters. The top and bottom geometries loft together to create a solid, and a central cylinder acts as an aligning tool and connection element. The central support connects to the outer geometry. The column is vertically sliced at intervals determined by the maximum printable height of print, and the G-Codes for each section are generated.

Findings

A section of the column was selected for printing. The initial expectations were for the test to generate deep crevices in the surface texture, but this only became evident higher up in the column. While the result was not entirely as intended, it provided an intriguing way to build wall thickness and

Test prints for column typology

Texture close ups

create a surface texture. Additionally, the connection details came out very brittle and should be incorporated into the components' overall design, be thicker, and provide more support. Observed shrinkage averages were 4.6% in the X and Y directions and 7.8% in the Z direction. The aesthetic texture results give a woven variable texture that works well with the variances from pressure deviations. Deformation occurs in the drying of two prints. The first was C1 which warped due to its thin walls. The second is C5, which dried with a tilt, making the entire column askew.

Designing for structural optimization is a good exploration opportunity for future design iterations. Biogenic future speculation for this typology would be exploring habitats for non-human species. The deep crevasses and varying surface textures create microclimates and provide variable habitats.

Aligned column image

Wall

Intention

This test intends to create a permeable and flexible divider of space that can be easily adapted.

Summary

Two-component designs connect to create this element. One acts as a connector and pivot point, and the other branches between the connectors. The walls of both components are derived from cylinders and use the same logic. A weaving texture is employed to achieve wall thickness and increase durability while handling. This texture is achieved by a continuous sine wave drawn around a circle. The sine wave represents the tool path and compresses to a degree that allows for bead articulation on the outer face of the print and provides enough adhesion between the print beads for adhesion. The next layer above rotates to align with a void below. The offsetting of solid and void is repeated throughout the height of the print to achieve a weaving

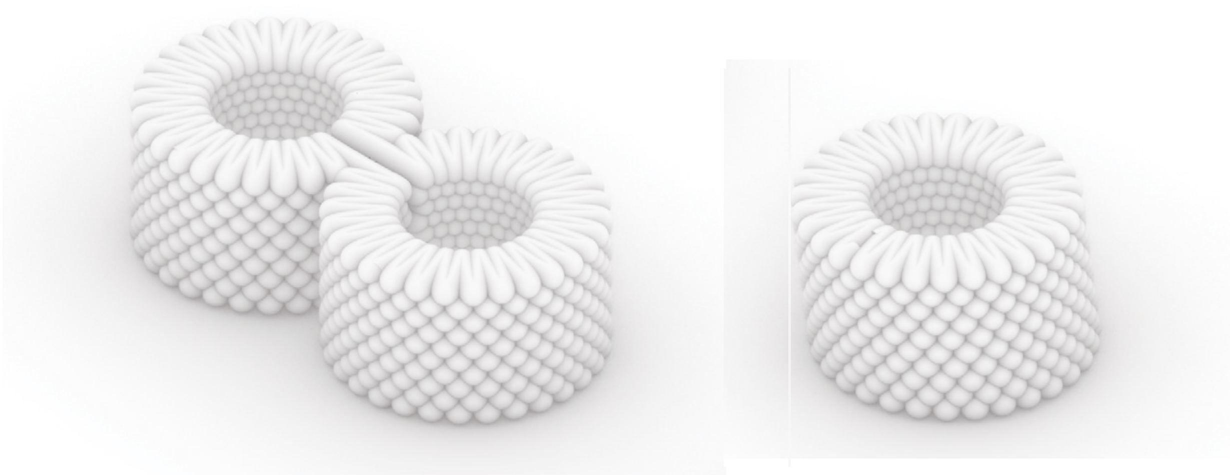
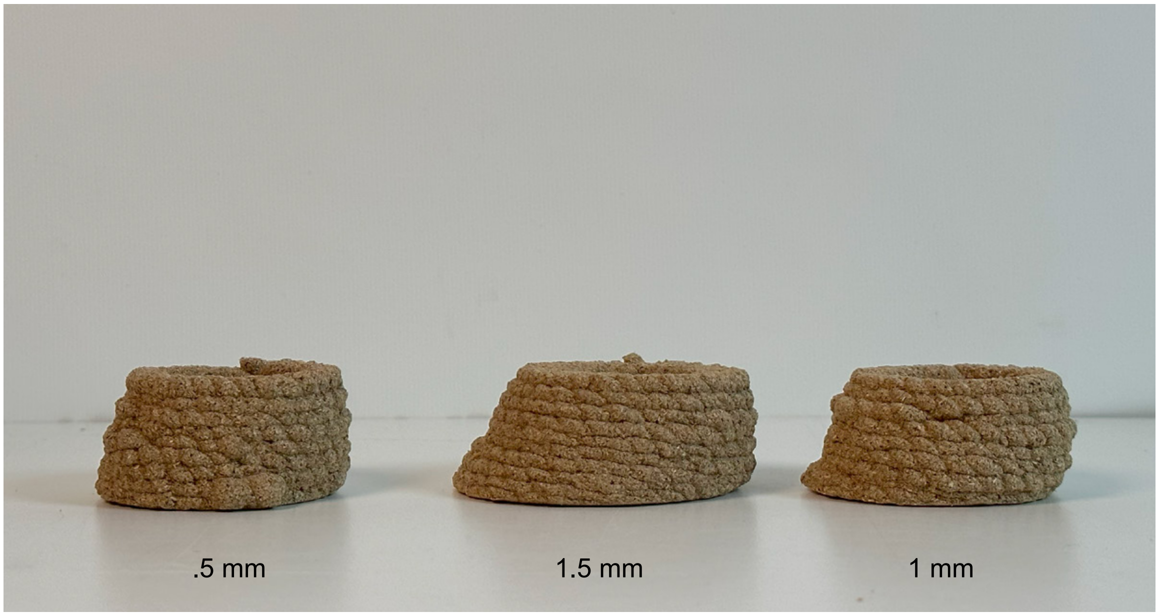
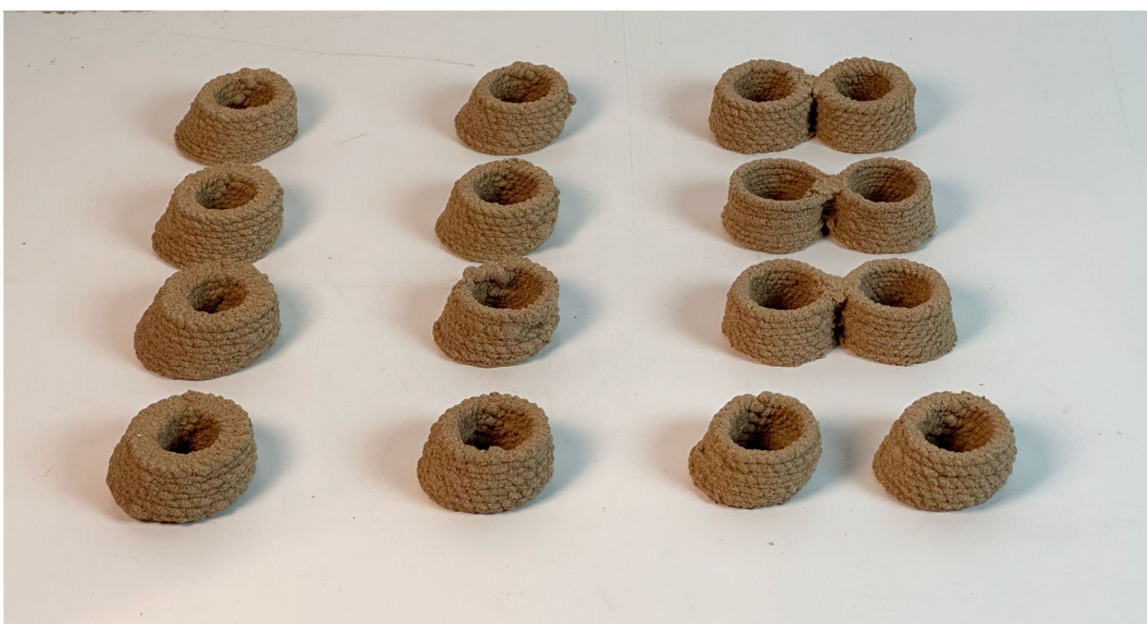


Diagram of extruded tool path visualization. Left is the connector component. Right is the branching component.



Tests of different layer offsets



Layout of printed components for wall assembly

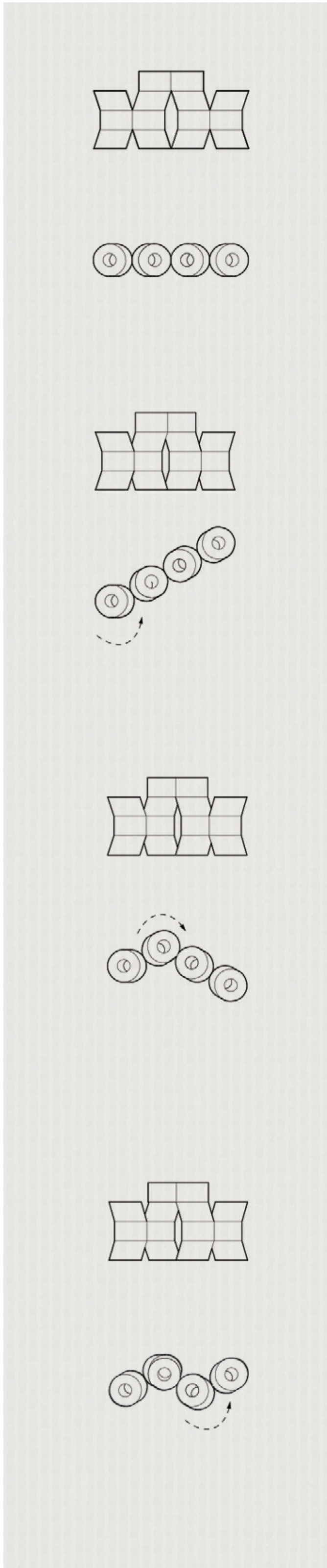


Diagram of pivot options

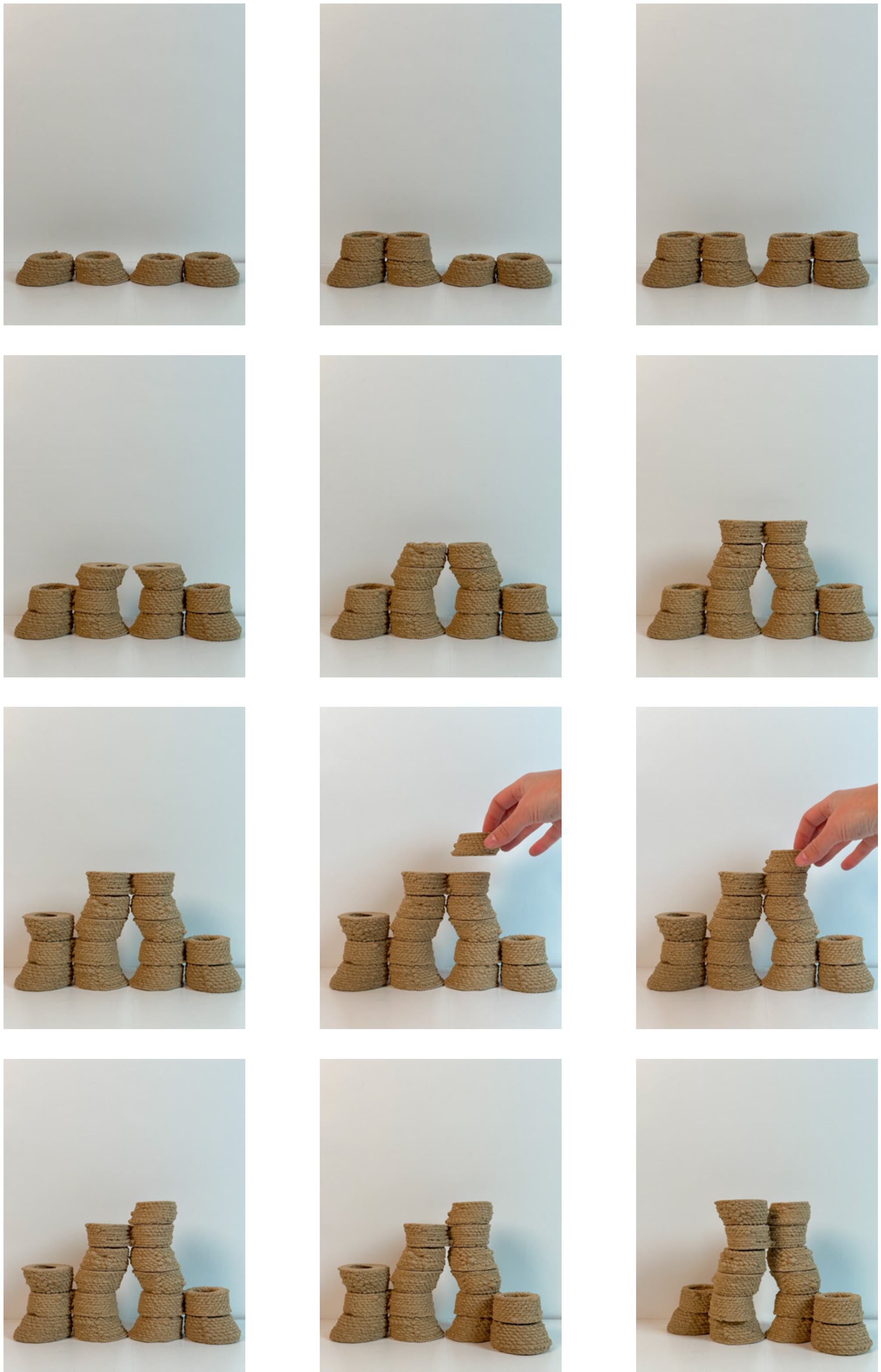
texture throughout the print. The interior of the cylinder is hollow to achieve adequate airflow while drying and act as a void or spine for connection detail in an assembly.

For these components, only two tool paths were generated. To create variation in the prints, the intention was to test this by adjusting the extrusion pressure while printing the material. The geometry of the connector components is two intersecting vertical cylinders. The tool paths of these two cylinders are connected, creating one component. The second component was achieved by moving each layer over incrementally to determine the optimum measurement that did not slump and created enough of an overhang for branching.

Findings

The system is designed to be built up to a desired size or composition. To test this, three connector components and ten branching components were printed. Despite thickening the walls, the connector pieces lacked adequate mass at the point where the two cylinders intersected and will need to be built up and revised in future iterations.

Controlling the size differentials via the extrusion rate resulted in a less defined outer wall and needed to be better suited for printing at this small scale. Biogenic future speculation for this typology maintains this language as the base connecting element and builds in variations to the branch lengths.



Iterative images of assembly

Assembled permeable wall set up

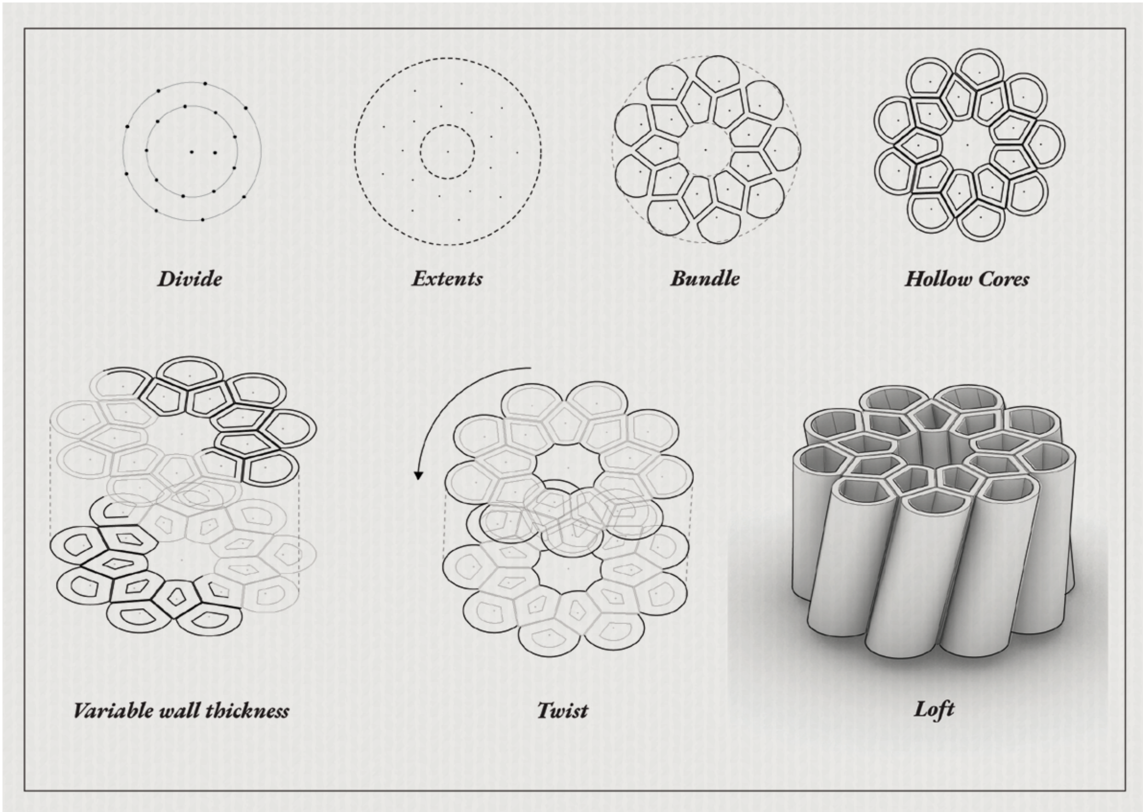


Diagram of fiber language transforming into cylindrical test component

Enclosure

Intention

The design intention for this typology takes inspiration from the biomechanics of the flax fibre.

Summary

Individual flax fibres are long hollow tubular elements that grow in bundles (Yan et al., 2014). These fibres contain a subtle twist that stems from their cellulose molecular composition (Ibid.). These biomechanical elements informed an abstracted typology from this typology. The printing language for this typology followed the key design prompts of bundle, hollow cores, and twist. In developing this language, two design iterations came about.

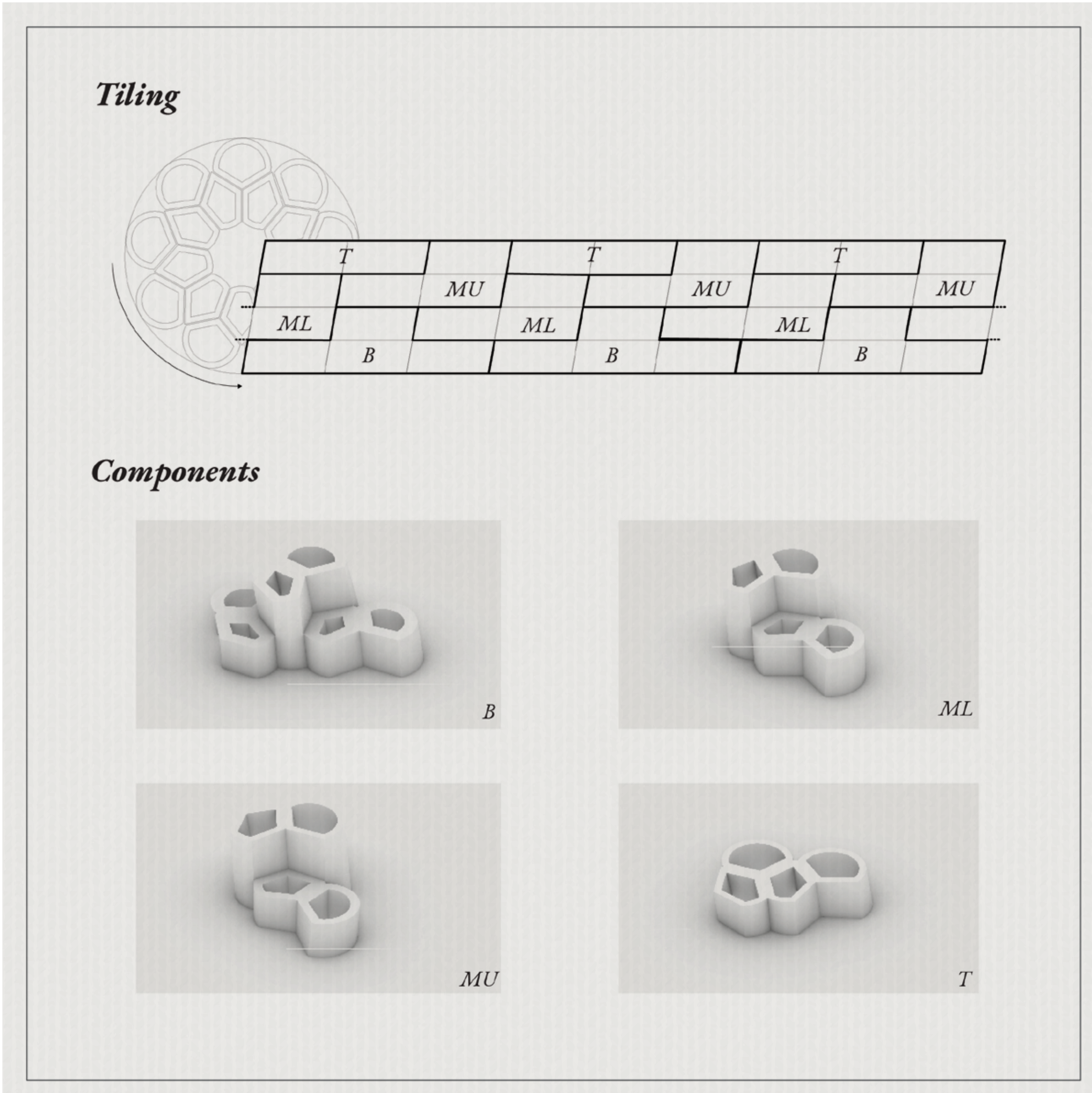


Diagram of titling pattern and components for first iteration of fibre printing typology

Print of bottom piece B

The first iteration tested this language and speculated on connection details. The print was designed as a tubular element to provide proof of concept for a design leading to an enclosure. To generate this element, a base geometry of a circle divides to create points for bundling, and the extent of the final footprint is drawn. Using a voronoi pattering, the bundles are created. Each cell is then offset to create the hollow cores. These are important for facilitating drying and providing connections. After the height of the print is established, a variable wall thickness is applied, with thicker

walls at the bottom that tapers towards the top. Lastly, a twist is applied by rotating the top layer. This form was broken up by applying an interlocking tiling pattern. The tiling pattern consisted of four components and three of each are required to create a completed element.

The second iteration was simplified and followed the key design prompts of bundles, hollow cores and a twist.

Findings

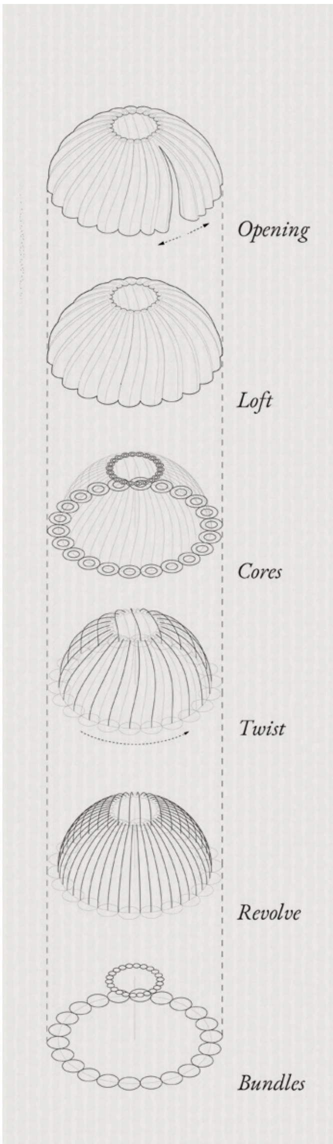
The first iteration proved to be too technical for this manufacturing method. A test bottom piece was printed. The print was too robust and collapsed under its weight. The second iteration performed as expected but would require additional mass to the connection points. Speculations of a biogenic future for this explored in the next chapter.

Print of second iteration of fiber typology print

Enclosure typology prints

Chapter 6: Architectural Demonstrator

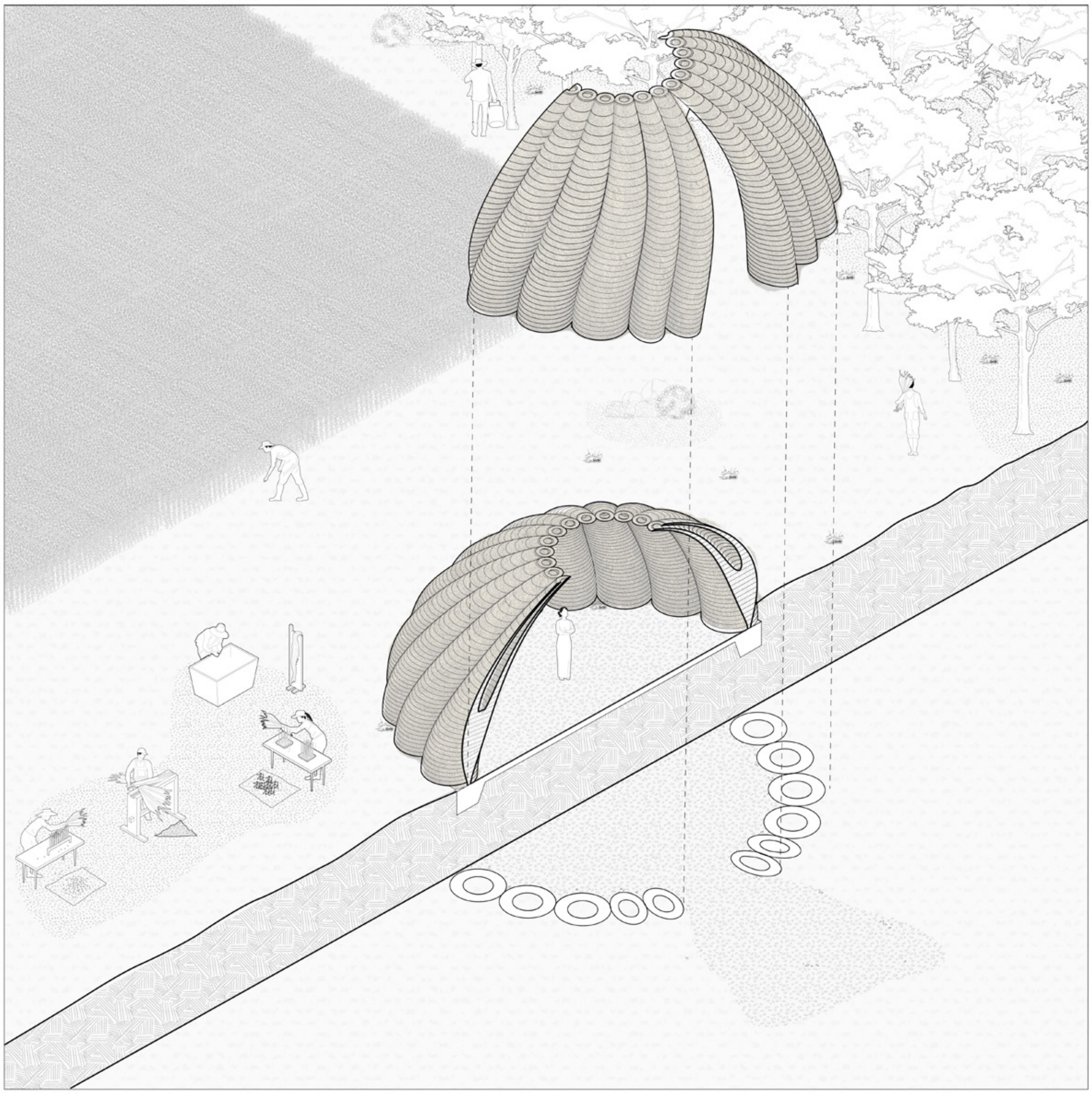
An architectural demonstrator uses the printing language established in the second iteration of the fibre typology to inform the design. To scale up from hand-held objects to a full-scale artifact, the printing system is speculated as a gantry system. This system facilitates a continuous print. The printer supports are erected around the footprint of the demonstrator and build up the structure layer by layer. This demonstrator shown here is envisioned as a temporary structure on a flax farm.



Pavilion design diagram

The site is chosen to branch the material scale with the local scale of this thesis. Given that biomaterials will eventually decay and compost, the structure will serve a temporary functional purpose, then at the end of its functional life will degrade and return to the ground from which it was sowed. Different additives can be incorporated into the mix to achieve desired effects.

Additional modifiers are added to the printing language. The footprint of the design is a circle which is divided and filled with bundled tubes. A smaller footprint is copied vertically to the desired height and shrunk to create an aperture. This allows the material mass of the structure to taper and thin out as the structure builds up. Thinning the material at the top helps to facilitate a steeper overhang. The organization of the structure is simple. The top an aperture allows for open air flow and terminates the wall height before the height of the structure becomes too high and collapses in on itself. Arcs between the upper and lower bundles create the shell of the space. This is where the printing language is employed and a twist is applied to the upper bundle. The



Axonometric of architectural demonstrator cores of the upper and lower bundles are hollowed out. These materials are lofted together, to represent the printed volume. The volume is built up by parallel tool paths that create the required wall thickness and mass. Lastly, an opening is created by compressing the tubes of the structure to allow adequate space for a person to enter.

The materiality of the structure is tactile and earthy. Continuous horizontal lines are softly visible from the printed layers. Each line is highly textured from the fine particles of the flax material. The mass of the structure dampens surrounding sounds.

Chapter 7: Conclusion

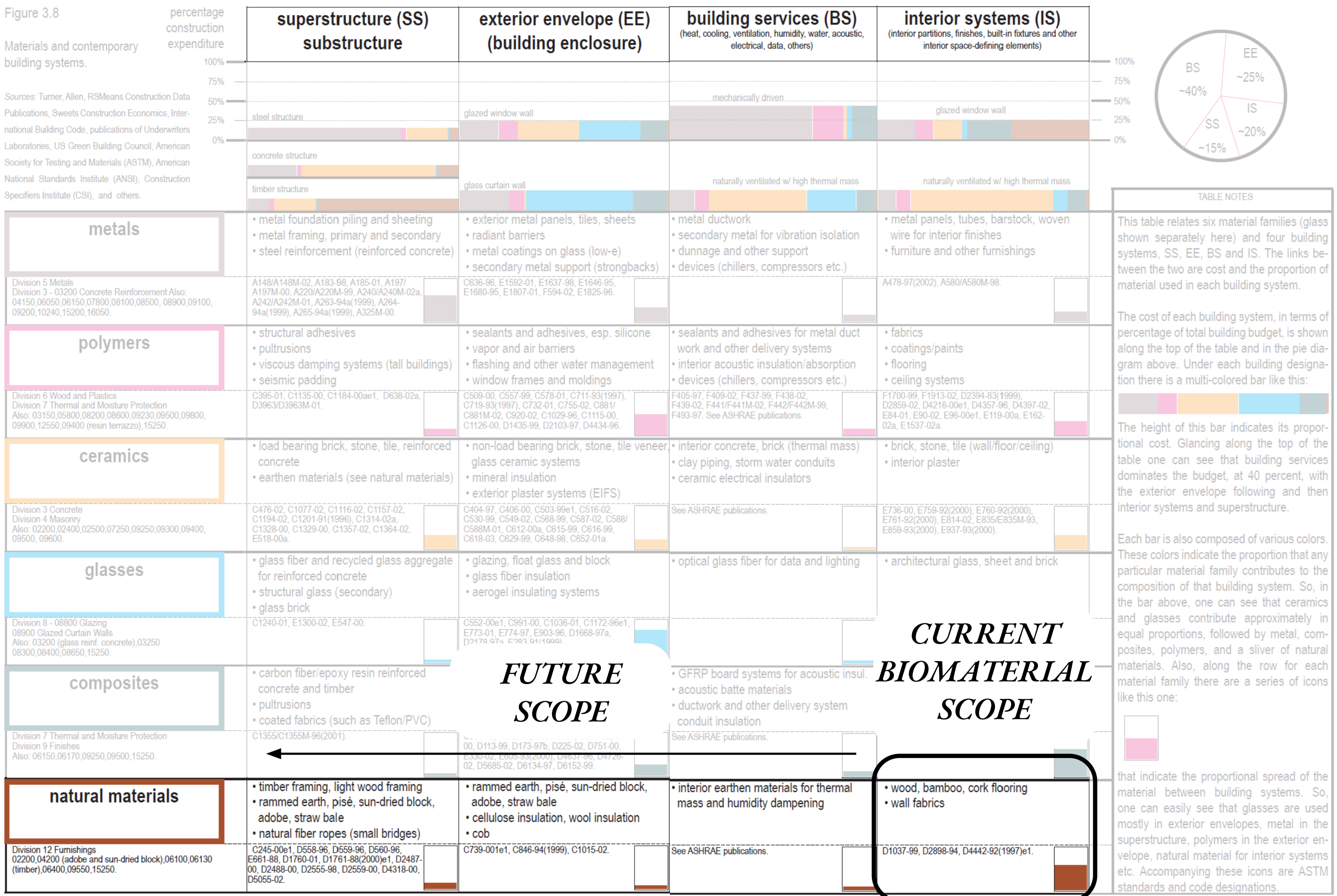
Material Scale

Reflecting on the material dialogue process, using the processed by-products with different printing methods is of interest. The fine shive powder is well suited for binder-jet explorations and there is potential for printing with the tow with a custom printing system.

The hydrophilic nature of the material is another opportunity for future development and exploration. Over the progression of printing in this thesis the early prints would dry and become rigid. However, as the seasons changed and the relative humidity of the coastal environment increased, the dry time extended and the final products developed a “squish”. Future experiments into working with the materials relationship to humidity would be an interesting exploration. This exploration can explore reducing the materials hydrophilic nature but testing resin binders or embrace this quality and explore an environmentally responsive material. Additional binders of interest for future exploration includes the use of organic resins, fungal or microbial binders.

Potentialities was chosen for this thesis title because there are endless possibilities in working with a new material. However, throughout this process it was important to maintain firm system boundaries to keep the inquiry on track. For this thesis the boundary was drawn to develop the by products for additive manufacturing. Wastes from textile production or discarded linens were not explored in this thesis.

Working through a digital fabrication workflow highlighted the limitations and opportunities of their use in design.



(Base image from Fernandez 2013)

Complex printed geometries are enticing but need to be developed slowly. Developing a printable material was a tedious process that involved moments of frustration and magic. I was constantly reminded to design incrementally based on the material capabilities rather than imposing an idea onto the materials.

Local Scale

This thesis contributed to a growing body of research that explores the architectural potential of flax by-products. Further and more detailed research is encouraged and needed to further explore more detailed applications. The methods used in this thesis to process the by-products followed a heat, beat, and treat method of processing that was required to prepare this material for additive manufacturing. Explorations into additional waste streams whose by-products are found in a particulate form are prime candidates for additive manufacturing.

Global Scale

The development of biogenic and biomaterials has a long way to go before full incorporation into architecture. Currently, these natural materials are ready for use at the interior stage and overtime and through development can branch into the enclosure stage.

Entanglements

This thesis speculated across scales in building a method for material development of a Biogenic Future. With the necessity to change our perspectives and practices in architecture, this thesis is envisioned as a contribution and framework to develop agricultural residues for architectural materials through digital fabrications. This method can be applied and tested in different local contexts. A change to the architectural material landscape will only happen incrementally over time and through investigation.

This method hybridizes two opposing themes in the current architectural discourse, technological innovation and biogenic materials. Digital fabrications allow for possibilities of new design languages and optimizations. Biogenic materials present an organic material palette that operates within ecological lifecycles. This hybrid and scalar method is intended to contribute to a world of further entanglements between human and non-human actors, in which architecture is the facilitator of those entanglements.

Appendix: Quantity Calculation

This test used the information available to determine what quantities of material are required to make a fixed amount of flax powder. This calculation is not a complete metric for measure and uses the material quantities available. This measurement intends to determine the land required to grow a set amount of flax powder.

During my visit to the processing centre at TapRoot Farms, I had the opportunity to process retted flax in the scutching machine. This process was too aggressive to extract viable longline fibres from the plants, but I did keep the materials. The product quantities were the roots of approximately 150 plants and 139.2g of shives. These measurements informed a ratio of shive weight per plant. The growing guide from the Flax Council of Canada was consulted to determine the spacing between plants to determine how many plants can grow on a one-meter square of land (Flax Council of Canada n.d.). Lastly, measurements were taken before and after the processing of shives into powder.

The conclusion of this test is that per 0.5m2 of land, 53-54 plants can grow, producing 50g of by-product shives. Processing this amount of shives will result in 37.5g of Flax powder, which is roughly the average size of one print.

While this information helps develop questions about the economy of scale, it also leads to speculation on how this metric compares to other materials.

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