CERAMIC 3D PRINTED PLANT-CENTRIC ARCHITECTURE

by
Yannik Sigouin

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored; see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

Yannik Sigouin was the sole author of this thesis, which was written under the supervision of Professor Linda Zhang. No portion of this document was written for publication. The thesis design work was done as a joint thesis collaboration, where exceptions to the sole authorship of this thesis are the production of ceramic prototypes, photographs, and select diagrams. Ceramic prototypes were co-created by Yannik Sigouin and Taylor Murray. Yannik Sigouin looked at the production of ceramic prototypes through studying plant typologies to inform parameters for the coding process, along with optimising digital to physical workflows. Taylor Murray looked at the ceramic prototypes through the lens of urban food growing, and was responsible for the system and component design. See chapter 2.7 for a detailed description of collaborative work.

ABSTRACT

This thesis utilises clay 3D printing to create 'plant-centric architecture', a concept defined by the author that aims to apply architectural design principles to methods of designing for plants. Traditionally valued for their aesthetic and psychological benefits, indoor plants are often objectified in contemporary architecture, serving as mere decorative elements rather than living organisms with intrinsic needs. This objectification reflects a broader trend in architectural practices where natural elements are manipulated to fit human desires, often at the expense of plant health and sustainability. On the other hand, hydroponic farming systems, which emphasise plant needs and maximise growth productivity, typically lack the aesthetic considerations of traditional architecture.

Plant-centric architecture seeks to bridge this gap by promoting a harmonious environment where the symbiosis between human and plant needs is architecturally envisioned and realised with ceramic 3D-printed design. Clay is historically significant for its material qualities and aesthetic appeal, often used at a range of design scales from building facades to flowerpots. 3D printing technology has revolutionised the design use of clay, creating intricate and functional designs catering to plant and human needs. By merging traditional craftsmanship with contemporary design, this approach aims to create environments that honour the vitality of plants, enhancing their health and sustainability while contributing to enriching spatial experiences for humans.

This thesis explores and evaluates the potential of architectural clay 3D printing in developing plant-centric architecture through iterative prototyping. By leveraging scientific understandings of plant architecture with iterative ceramic 3D printed prototyping, this work has the potential to set a new standard in architectural design for plants. The work envisions fostering spaces that nurture both plants and humans, initiating a new dialogue on the future of posthuman architectural design.

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LAND ACKNOWLEDGEMENT

I acknowledge that I live and work on the traditional territory of the Neutral, Anishinaabeg, and Haudenosaunee Peoples. The University of Waterloo School of Architecture is situated on the Haldimand Tract, the land granted to the Six Nations that includes six miles on each side of the Grand River. It is through uplifting the voices of Indigenous students and faculty that we may reconcile with our past and present relationships with colonialism. In order to build a shared future of peace and respect, it is our responsibility to learn these histories and reconcile even if Indigenous communities do not have the capacity to guide us.

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CHAPTER 1 – INTRODUCTION

1.1 – DEFINING PLANT-CENTRIC ARCHITECTURE

"Plant architecture is defined as the three-dimensional organisation of the plant body. For the parts of the plant that are above ground, this includes the branching pattern, as well as the size, shape and position of leaves and flower organs. Plant architecture has long been the only criterion for systematic and taxonomic classification, and, even today, it is the best means of identifying a plant species. But it is also of major agronomic importance, strongly influencing the suitability of a plant for cultivation, its yield, and the efficiency with which it can be harvested."[1]

Architectural discourse is human-dominant, where the design approach is to optimise relationships between people, spaces, and buildings. Contrasting this common understanding of architecture as a profession is the scientific use of architecture, specifically in plants. The introductory quote on plant architecture reduces architecture to the aspects that make up a plant, eliminating the habitation aspect that human-centric architecture possesses. By comparing the use of 'architecture' as a term in the fields of architecture and science, this thesis defines a new term called 'plant-centric architecture'. Where plant architecture involves what makes up a plant, plant-centric architecture uses the organisation of the plant body and its needs as the primary driver for design.

Indoor plants are cultivated and maintained indoors, such as in homes or offices. These plants typically do not grow too much and require little light, water, and humidity to thrive.[2] Historically, the integration of flora within indoor spaces can be traced back to ancient civilisations, where plants were used both for symbolic decorative purposes and for their perceived health benefits[3] (Figure 1.1.1). In modern times, indoor plants have become ubiquitous, often serving interior spaces as both aesthetic enhancements and tools for improving air quality and human psychological well-being.[4] However, this modern perception usually overlooks the plants' dignity, treating them more as objects or decor items for humans rather than as living organisms with needs and life cycles[5] (Figure 1.1.2).

This objectification of plants is reflected in the development of architectural practices. Architecture often uses plants within interior spaces as design element tools to achieve a particular aesthetic or feel without necessarily considering the natural requirements of the plants.[6] This trend reflects a broader architectural approach where the natural world is often manipulated to fit human needs and desires, often at the expense of the health and sustainability of the plants involved.[7] Examining how plants are incorporated into building designs reveals contemporary architecture's broader practices and priorities, highlighting a need for approaches that respect and integrate the natural environment more meaningfully.

1. Reinhardt and Kuhlemeier, "Plant Architecture"
2. Léon & George, "Leafy Legends: The Vibrant History of Houseplants"
3. Wynne, "A Potted History: How Houseplants took over our Homes and our Hearts"
4. Williams, "Taming the Potted Beast: The Strange and Sensational History of the Not-So-Humble Houseplant"
5. Sparke, "Nature Inside: Plants and Flowers in the Modern Interior"
6. Horwood, "Potted History: The Story of Plants in the Home"
7. Bailey and Bailey, "The Hidden histories of Houseplants: Fascinating Stories of Our Most-Loved Houseplants"



Figure 1.1.1 - An artistic depiction of the Hanging Gardens of Babylon, 1886 CE, one of the Seven Wonders of the Ancient World, showcasing the lush vegetation and grand architecture that characterised the legendary gardens. This illustration, created by Ferdinand Knab, was published on July 26th, 2018, by the World History Encyclopedia.



Figure 1.1.2 - Mrs. Agnes Bergström posing on a lounge chair in Agnesviks Herrgård outside Filipstad. The photograph, taken around 1920 by Sven Johan Ölander, captures a richly decorated interior filled with various plants and ornate furnishings, reflecting the opulence of the period. Photo owned by Värmland Museum and published to Digital Museum on October 14th, 2016.

The prevalent trend of treating indoor plants as aesthetic objects within architecturally designed spaces underscores a broader issue of objectification in our built environments. This utilitarian view, however, contrasts sharply with more plant-centric approaches such as hydroponic indoor farming. Hydroponics is a method of growing plants without soil, using mineral nutrient solutions in water, and shifting the focus back to the plants, emphasising their needs and life cycles[8] (Figure 1.1.3). This technique not only allows for precise control over nutrients, lighting, and water, all tailored to maximise the health and growth productivity of the plants, but also dramatically increases yield in a limited space, showcasing a profound sensitivity for the plants as living entities.[9] Despite these benefits, hydroponic systems often lack architectural design, typically focussing purely on functionality without integrating the aesthetic and human-centric elements that traditional architecture might offer.

There is a significant opportunity here for architects to bridge this gap, crafting spaces and artefacts that enhance the efficiency of hydroponic farming and the aesthetic and emotional well-being of human occupants. By considering how architectural elements can complement hydroponic systems, designers can create environments that honour the dignity of plants, akin to how we design spaces for human use. This thesis will develop design approaches that are not only sustainable but also enriching and harmonious for all occupants, plants and humans alike.

In seeking harmony between indoor plant environments and human spaces, the innovative application of ceramic architecture emerges as a promising avenue. Historically, clay has been a fundamental material in plant-centric and human-centric design, revered for its natural origins, durability, and aesthetic appeal[10] (Figure 1.1.4). This tradition of using clay is now being revolutionised by advancements in 3D printing technology,[11] which allows for creating intricate ceramic forms that were once impossible or too labour-intensive to achieve through conventional methods.

Clay 3D printing merges traditional craftsmanship with contemporary design, enabling the production of complex structures that can be tailored to the specific needs of both plants and humans. This technique enhances the functionality and interactivity of spaces, allowing for more organic and fluid designs.[12] The use of clay 3D printing can ensure that these elements can be implemented to create environments that are as beneficial to plants as they are to human occupants.

This thesis utilises clay 3D printing to create plant-centric architecture, as defined by the author, to apply architectural design principles to methods of designing for plants. This thesis not only seeks to showcase the potential of integrating advanced technology with natural materials but also looks to explain new standards in design. Architectural design principles are used to leverage the scientific understanding of plant architecture as guiding parameters to dignify plant-centric design. The author's defined terminology of plant-centric architecture seeks to promote a harmonious environment where the symbiosis between human and plant needs is architecturally envisioned and realised, fostering moments in spaces that nurture both.

8. Baras, "DIY Hydroponic Gardens: How to Design and Build an Inexpensive System for Growing Plants in Water"
9. Loewer, "Hydroponics for Houseplants: An Indoor Gardener's Guide to Growing Without Soil"
10. ACAW, "Architectural Ceramic Assemblies Workshop: Bioclimatic Ceramic Assemblies I"
11. Association for Robots in Architecture, "Robotic Fabrication in Architecture, Art and Design 2014"
12. Rael and San Fratello, "Printing Architecture: Innovative Recipes for 3D Printing"



Figure 1.1.3 - A worker tends to a variety of leafy greens growing in a greenhouse using hydroponic methods. This sustainable agriculture technique allows for efficient water usage and high-density planting. Photo taken by Sasin Tipchai and published to Pixabay on November 1st, 2016.

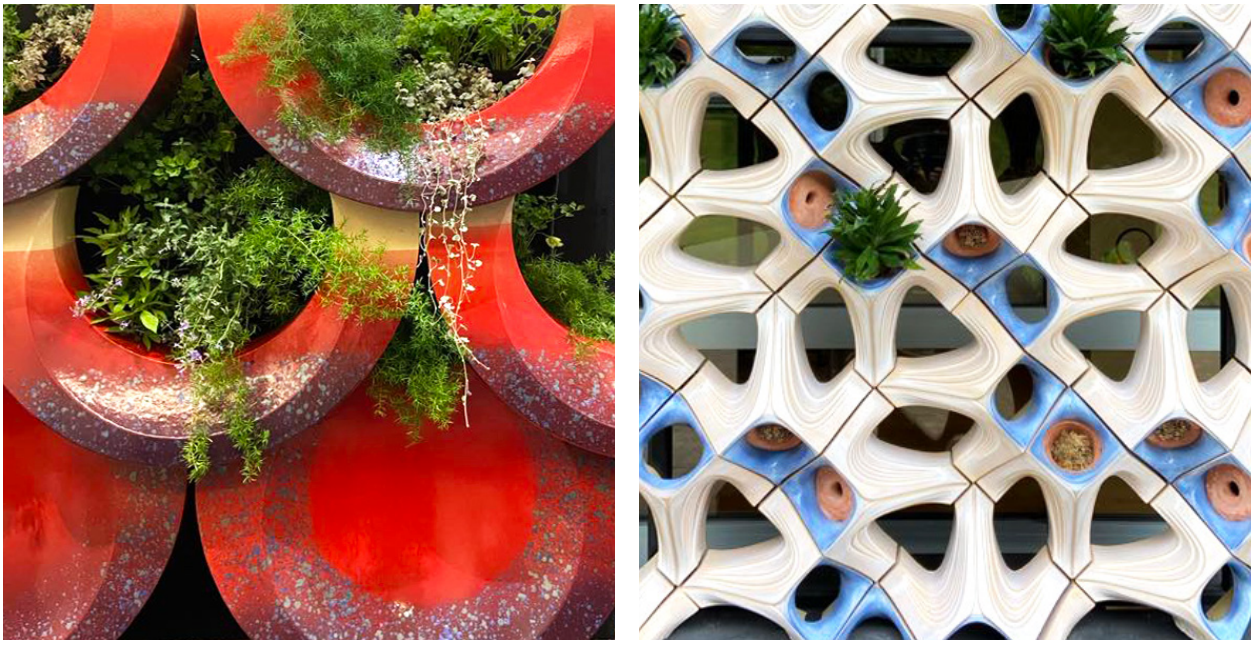


Figure 1.1.4 - Ceramic architecture assembly designed by Eric Perry Architects, ACAW 2023 (left), and Cookfox & Buro Happold, ACAW 2021 (right). Both assemblies were fabricated by Boston Valley Terra Cotta. Photos by author Yannik Sigouin during the Architectural Ceramic Assemblies Workshop (ACAW) in Buffalo, NY, USA, on August 17th, 2023.

CHAPTER 2 – METHODOLOGY & OBJECTIVES

2.1 – RESEARCH OBJECTIVES

This thesis aims to achieve the following research objectives:

RO1 Design and Craft: Utilise clay 3D printing to apply architectural design principles to indoor plant-growing systems, including the aesthetic and detail intricacy of clay 3D printing. Aim to address architectural design qualities of indoor farming systems, including hydroponic plant farming.

RO2 Scalability of Designing Architecture: Apply architectural design principles to smaller-scale needs beyond human-scale needs. Place plant vitality at the centre of the design process and criteria to develop architectural design principles that differ from the human-centric scale of buildings and urban fabrics.

RO3 Adjustable Hybridised Systems: Utilise adjustable systems to respond to plant morphological and health cycle needs that operate at a different time scale than humans and thus require adjustability. Prioritise plant typologies to lead design parameters, shifting static indoor human-centric systems to responsive plant-centric systems.

2.2 – DESIGN PROTOTYPING OVERVIEW

The plant-centric architecture prototypes were developed through an iterative clay 3D printing process that tested component designs by creating several models (Figure 2.2.1). Once a base component that satisfied general principles for plant design was selected, further iterations were designed to cater to other plant typologies. An iterative process was selected for this research due to the unique properties of clay as a material and plants as a subject. Clay is 3D printed when it is in a wet, fluid state, and therefore, initial design concepts and computer modelling projections often differ from the 3D printed components. The process of continually 3D printing, evaluating, and adjusting the designs allows for the characteristics of clay to be leveraged in the plant-centric design in a way that would not otherwise be possible. Prior to the iterative 3D printing process, plant research and schematic design phases determined the required system components and their relationship to one another. Then, in the design development phase, 3D printing of the components was done through two key iterations of large scale prototyping.

The first prototype iteration used the Scara V4 3D printer to fabricate a series of test prototypes at 0.75:1 scale. The Scara 3D printer is ideal for rapid prototyping as it uses a large 3600 cc extruder tube, which can create many 3D prints in succession. This stage is intended to develop each component's massing, proportional relationships, and structural connections. The second prototype iteration used the Scara V4 3D printer and the Lutum 4.6 3D printer to develop components at a 1:1 scale. The Lutum 4.6 3D printer uses a 1400 cc extruder tube and can produce high-detail-quality prints. The Lutum 4.6 3D printer was used to create all printed components in this stage, except for components that required more than 1400 cc of clay, which were produced using the Scara V4 3D printer. The second iteration is intended to develop the detailed quality of each element and create precise structural connections throughout the system. All prototypes were created using white, mid-fire stoneware (PSH 516). Each clay 3D print used a 3mm nozzle and a 2mm layer height.

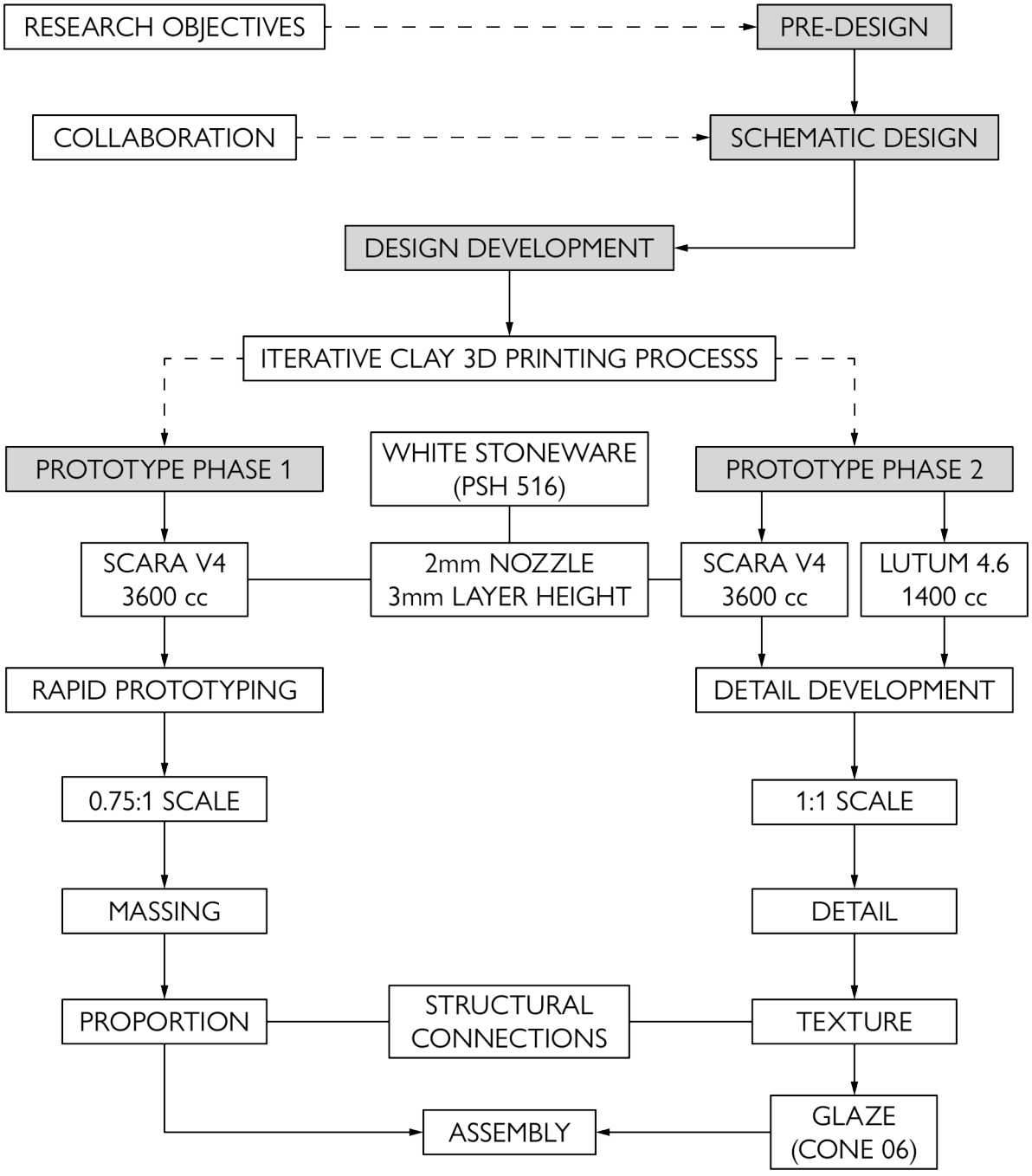


Figure 2.2.1 - Overview of methods used to develop the plant-centric architecture prototypes. Diagram by Yannik Sigouin.

2.3 – RESEARCH WORKFLOW

The research phase involved using plant typologies and architectural design methodologies to generate design principles for plants. In the realm of architectural design, principles such as form, function, and materiality are crucial in creating structures that are not only aesthetically pleasing but also highly functional.[13] Furthermore, Gestalt principles of proximity, similarity, continuance, and closure were considered to elevate the perceptive experience of the design.[14] These principles were applied to designing for plants to explore an innovative pathway to create aesthetically sustainable and efficient growing systems. This phase explored integrating architectural and psychological design principles with plants' structural and environmental needs. This plant-centric architectural prototype focused on small plant typologies, such as herbs and leafy greens, for preliminary testing. The plant-centric design aimed to leverage clay 3D printing and incorporate a Deep-Water Culture (DWC) hydroponic Kratky system, augmented with an adjustable grow light system.

It is essential to understand the structure of plants[15] to create a plant-centric design that caters to plant vitality (Figure 2.3.1). Prototypes addressed the following vital parts of plants:

- Roots: Responsible for water and nutrient uptake, anchoring the plant.
- Stem: Supports the plant body and transports fluids between roots and leaves.
- Leaves: The primary site for photosynthesis, converting light into chemical energy.
- Flowers/Fruits: Reproductive structures, although less relevant for leafy greens and herb-focused designs.

Incorporating architectural design principles into plant-centric design requires understanding plant biology and environmental needs. By leveraging clay 3D printing and the Kratky hydroponic system, the final plant-centric architecture prototype addresses the physical and nutritional requirements of small indoor plants like herbs and leafy greens. Integrating a dynamic system that combines a grow light with hydroponics further enhances the prototype's design flexibility and efficiency. This approach supports optimal plant growth and exemplifies how innovative architectural design can harmonise functionality, sustainability, and aesthetics when designing for plants.

13. Foster, "The Principles of Architecture: Style, Structure and Design"
14. Koffka, "Principles Of Gestalt Psychology"
15. Bowes and Mauseth, "Plant Structure"

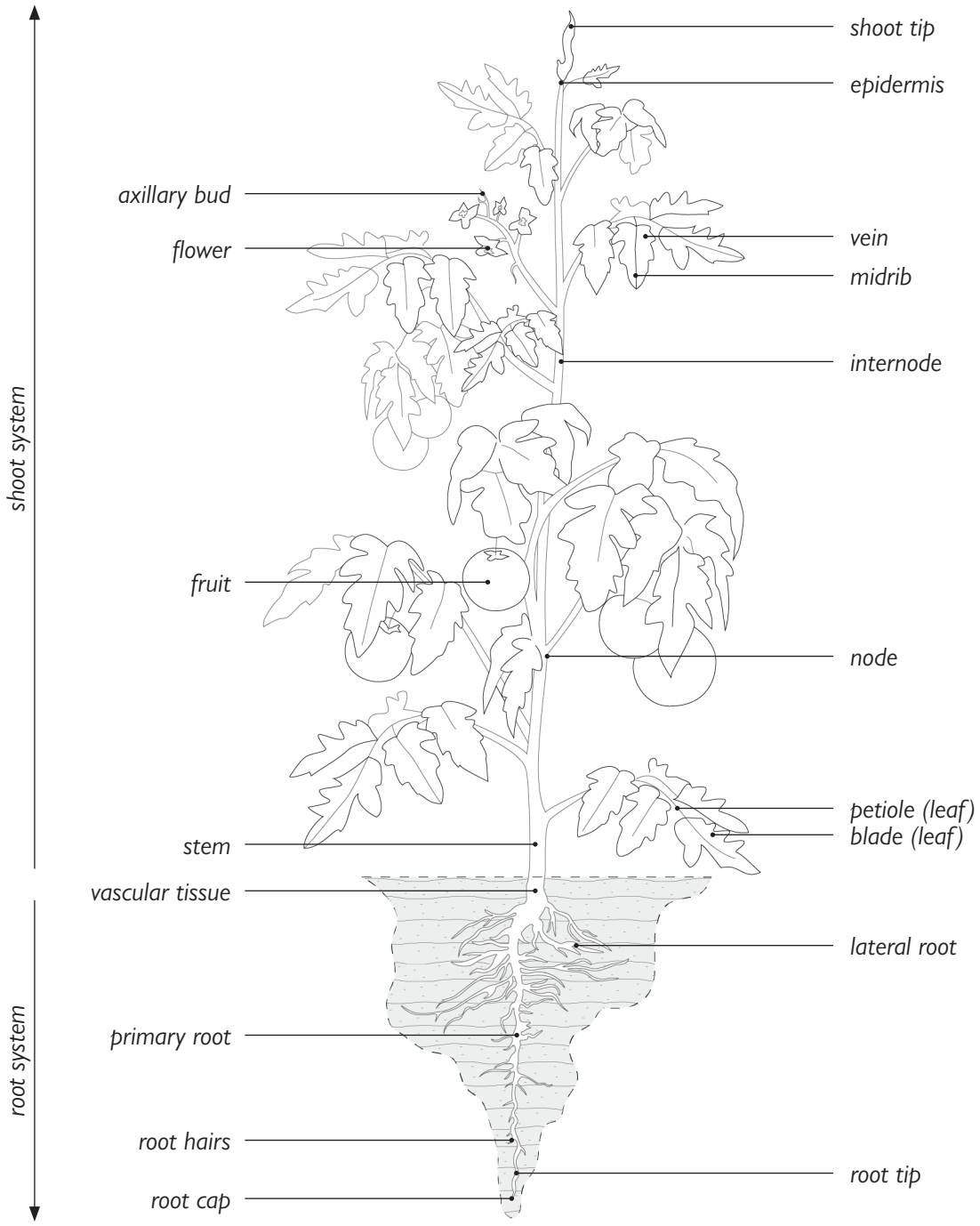


Figure 2.3.1 - Vital parts that make up the overall structure of plant typologies.
Diagram by Yannik Sigouin.

2.4 – DIGITAL WORKFLOW

The schematic design phase used hand sketching to test design options for the formal and organisational compositions of the prototype (Figure 2.4.1). Following this, the 3D modelling software Rhinoceros 3D was used to model the base component. Once this was complete, the graphical algorithmic modelling plug-in Grasshopper was used to generate a series of contour lines corresponding to each model's geometry. The contour lines are the 3D printer's toolpath, while the distance between the lines is the layer height. The tool path lines were further adjusted in Grasshopper to develop the aesthetic details of the system by using additional scripts to experiment with geometric rotations, surface gradients, textures, and patterns. Once the aesthetic details of the system were complete, the model was prepared for 3D printing. A final script was used in Grasshopper to produce a custom G-Code. The G-Code is a series of spatial coordinates describing the massing of the 3D model that acts as a set of instructions for the 3D printer.[16] The G-Code was verified in the Cura slicer software to ensure the massing and the tool path code were correctly produced. Following this, the model was uploaded to the clay 3D printers.

16. García Cuevas and Pugliese, "Advanced 3D Printing with Grasshopper, Clay and FDM"

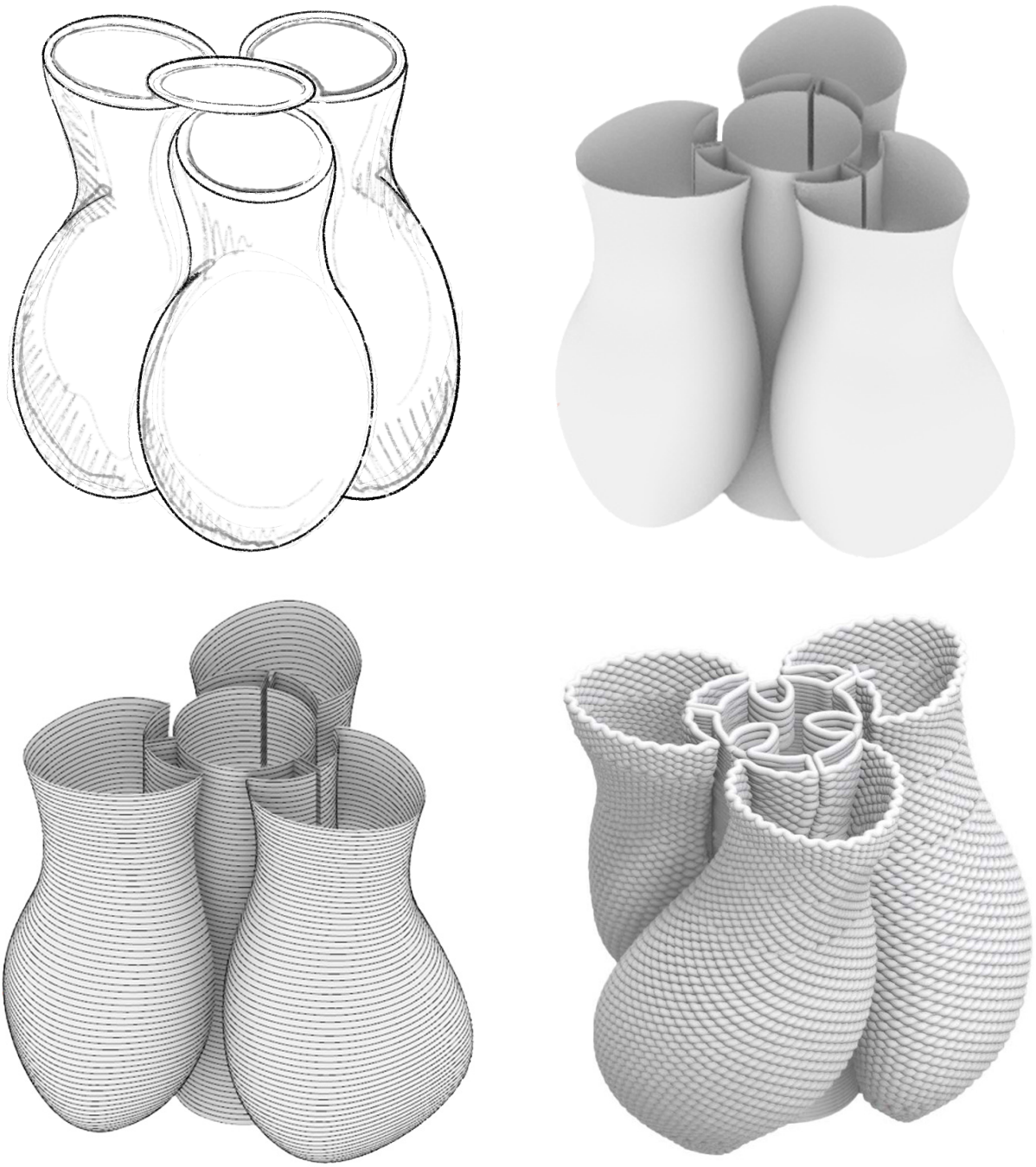


Figure 2.4.1 - Hand sketching was used to test the massing of the plant-centric prototype components (top left). Once a desirable massing was drawn, it was 3D modelled in Rhinoceros 3D (top right). After the massing was digitally envisioned, Grasshopper was used to generate the tool path (bottom left) and then further adjusted to enhance the aesthetic qualities (bottom right).

2.5 – PHYSICAL WORKFLOW

After creating the digital files, the Scara V4 and Lutum 4.6 clay 3D printers and the clay must also be prepared for 3D printing (Figure 2.5.1). To prepare the clay for use, its water content needs to be increased to improve its plasticity. The clay blocks were cut into 1" cubes and stored in a water-filled bucket. The ratio was 1 cup of water to 10 kg of clay. The clay was then left to saturate for at least 24 hours before being removed and recombined into a solid mass by wedging. Wedging the clay is critical to ensure the added water is evenly distributed and remove any air pockets. The presence of air pockets can severely damage 3D print quality, as they become highly pressurised and tear through the 3D print when pushed through the nozzle.

After wedging, the clay was shaped into a cylinder and fitted into a metal extruder that pushed the clay into the acrylic tube used for 3D printing. Once the tube was full of clay, a 3 mm nozzle and the 3D printer motor were fastened. The clay and clay 3D printers are now prepared for 3D printing (Figure 2.5.2).

During 3D printing, each prototype is produced on a medium-density fibreboard (MDF) batt, which was used to transport the 3D print to a drying tent once it was complete. Occasionally, a heat gun was used to dry pieces during 3D printing and provide rigidity to the clay, which helped to prevent the pieces from collapsing. Any prototypes that were unsuccessful due to imperfections or print-collapse could be entirely reclaimed, making this process zero waste. Prototypes that were successful needed to be dried in a drying tent for approximately one week before they were able to be loaded into the ceramic kiln for cone 06 bisque firing. The size of the 3D prints was limited by the interior dimensions of the Euclid CF-255 kiln, which are 22" long by 22" wide and 27" high. The clay is bisque fired in the kiln at cone 06, which is 999 °C. The observed shrinkage rate after bisque firing was approximately 12 - 15%.

Following the bisque firing, the pieces were removed from the kiln and are solid, brittle, and slightly porous. The pieces were then dipped in a bucket filled with mid-range glaze, making the vessels impervious to water and adding colour to the surfaces. They were again loaded into the kiln and fired at cone 6 (1222 °C) for the first attempt, which resulted in failure. The second glaze fire attempt was successful, as the pieces were dipped in a low fire glaze and fired at cone 06 (999 °C). The pieces shrink again by approximately 10 - 15%. Following this, the ceramic pieces were complete. This process is the standard method used in this research to produce all ceramic prototypes.



Figure 2.5.1 - Clay is stored in a bucket with excess water. Once the clay is saturated, it is hand-wedged to remove air pockets. The clay is pushed through an extruder into an acrylic tube used for 3D printing. The nozzel and motor are attached to the clay tube and then connected to the clay 3D printer. Photos taken by Dani Grabke on January 21st, 2024.

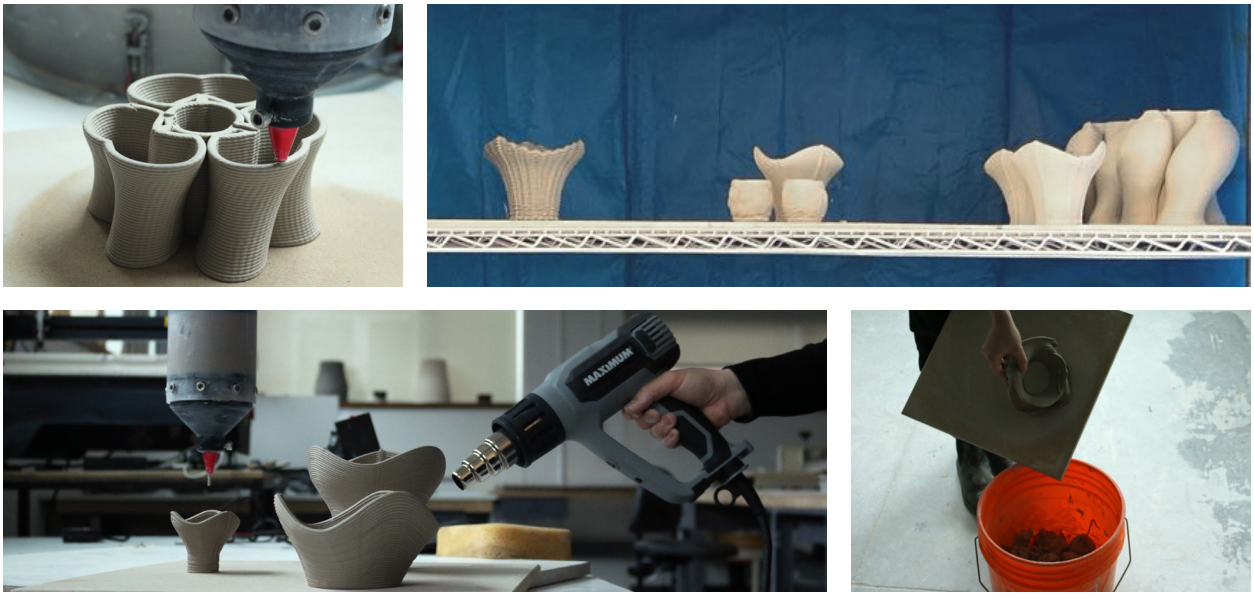


Figure 2.5.2 - The 3D printer has been prepped and is ready to clay 3D print. Each prototype is produced on an MDF batt and transported to a drying tent once complete. Occasionally, while 3D printing, a heat gun was used to dry the pieces, providing rigidity to the clay. Any prototypes that were unsuccessful were reclaimed. Photos taken by Dani Grabke on January 21st, 2024.

2.6 – DESIGN PARAMTERS & CONSTRAINTS

2.6.1 – Design Principles & Fabrication Constraints

The physical and digital workflows include four key design principles and fabrication constraints that affect the design capabilities of the 3D printed ceramic components:

- Clay 3D printer's extruder tube size is 3600 cc on the Scara V4 clay 3D printer and 1400 cc on the Lutum 4.6 clay 3D printer. A continuous 3D print that requires more clay than can be contained in the 3D printer's extruder tube is impossible.
- Size of the clay 3D prints cannot exceed the interior dimensions of the Euclid CF-255 kiln shelves, which are 22" long by 22" wide and 27" high (Figure 2.6.1.1).
- Shrinkage rates of the clay reduce the size of the final printed artefact. The observed shrinkage rate for the white stoneware is approximately 12-15% after bisque firing and 10-15% after glaze firing.
- Maximum 45° of overhang before potential of collapsing due to plasticity.



Figure 2.6.1.1 - Loaded Euclid CF-255 kiln at the University of Waterloo School of Architecture.
Photo by Taylor Murray

2.6.2 – Clay 3D Printing

Clay 3D printing as the choice of material and fabrication method is due to its combination of rich historical use, natural properties, and modern innovative capabilities. Clay is ideal for creating intricate, functional, and aesthetically pleasing objects that enhance the relationships between humans and indoor plants. Furthermore, the design process of working with clay for 3D printing is a must due to its dynamic nature, allowing for continuous iterative prototyping and refinements. This method of work can prototype rapidly, test, and modify designs in a living, evolving process that integrates creativity and functionality (Figure 2.6.2.1).

Clay as a material	Clay is eco-friendly, abundant, and versatile. It is malleable when wet and hardens to a durable state, making it suitable for functional and aesthetic applications in 3D printed projects.
Aesthetics of clay	Clay offers a natural and earthy aesthetic that complements indoor plants. Its texture and colour variations add visual interest and can be customised with glazes and finishes to match any decor.
Traditional human use of clay	Humans have used clay for thousands of years to make pottery, bricks, and sculptures. This historical context adds cultural and artistic value to modern 3D-printed clay objects, connecting past and present techniques.
Historical use of clay with plants	Clay pots have traditionally been used for planting due to their breathability and ability to regulate moisture. This historical use underscores the practicality and suitability of clay for plant containers.
Symbolic relationship between humans and indoor plants	Clay fosters a deeper connection between humans and plants as a natural material. It is porous, allowing plants to breathe and thrive, enhancing the symbiotic relationship in indoor environments.
Digital side of clay 3D printing	Using CAD software and digital modelling tools allows precise control over the design process. Parameters can be adjusted easily, and complex, custom designs can be created and iterated quickly.
Global geometry that only 3D printing can do	3D printing with clay enables the creation of complex geometries and intricate designs that are difficult or impossible to achieve with traditional methods, allowing for innovative and unique plant pot designs.
Ability to create an aggregate of parts	3D printing allows for the seamless integration of multiple components into a single cohesive unit. This is ideal for creating modular or multifunctional plant-related structures such as interconnected pots or self-watering systems.
Overall process	The process involves designing the object digitally, preparing the clay mixture, printing the object layer by layer, and finally firing or air-drying the printed piece. This combination of digital and manual steps ensures precision and is in the personal interest of the author.

Figure 2.6.2.1 - Material table overview of why clay 3D printing was chosen for this work.
Table by Yannik Sigouin.

2.7 – COLLABORATIVE DESIGN WORK

The ceramic prototypes were co-created as part of a joint thesis between author Yannik Sigouin and work partner Taylor Murray (Figure 2.7.1). Under the supervision of Professor David Correa, Taylor Murray looked at the ceramic prototypes through the lens of urban food growing.[17] The two theses were worked on in parallel, where Taylor Murray contributed more intensively to the hydroponics and system design. The author Yannik Sigouin contributed to the production of ceramic prototypes through studying plant typologies to inform parameters for the coding process, along with optimising digital to physical workflows. The collaboration strengthened the overall workflow and design results due to the diverse skillsets and perspectives that both contributors offer.

17. Murray, "Re-Imagining Indoor Gardening Systems: Ceramic Light Fixtures as Food Growing Typologies"



Figure 2.7.1 - Image of the collaboration between the author Yannik Sigouin (left) and collaboration partner Taylor Murray (right). Photo by Andrew Campbell at the University of Waterloo School of Architecture.

CHAPTER 3 – CASE STUDIES

3.1 – DESIGN & CRAFT OF CERAMIC 3D PRINTED ARTEFACTS

State-of-the art design research in clay 3D printing offers an innovative approach to creating artefacts that seamlessly blend aesthetics with functionality. This emerging technology revolutionises the production process and expands the possibilities for designers to craft unique and personalised artefacts that enhance interior spaces. Clay 3D printing opens new creative avenues, allowing designers to experiment with intricate forms, textures, and patterns previously unattainable through traditional methods.[18] Moreover, using clay as a material offers inherent benefits for indoor plant pottery, including breathability, moisture retention, and natural insulation, making it an ideal choice for creating planters that promote healthy growth.[19]

Drag & Drop, a design collective by Madalin Gheorghe and Dragos Sabareanu, specialising in sustainable and modular design solutions, utilises clay 3D printing to create customisable pottery for indoor plants (Figure 3.1.1). Their approach prioritises environmental consciousness and resource efficiency, focussing on minimising waste and maximising utility. Using modular components and parametric design principles, Drag & Drop crafts ceramic 3D printed planters that can cater to various plant sizes and spatial configurations, offering a versatile and eco-friendly solution for indoor gardening enthusiasts.[20]

StögerHaus by Josef Stöger is a design studio renowned for its fusion of traditional craftsmanship with cutting-edge technologies, embracing clay 3D printing to bridge the gap between past and present (Figure 3.1.2). Josef's work embodies a harmonious blend of artisanal techniques and digital fabrication methods, resulting in ceramic 3D-printed sculptures that exude timeless elegance and sophistication. StögerHaus creates beautiful artefacts that honour heritage while embracing innovation by marrying traditional pottery-making processes with the precision and efficiency of 3D printing.[21]

Clay 3D printing represents a transformative approach to creating thoughtful artefacts that enhance pottery and lighting fixtures' aesthetic and functional aspects. The two bodies of work by Drag & Drop and StögerHaus demonstrate how clay 3D printing is used to push the boundaries of design innovation while respecting tradition and sustainability. As clay 3D printing continues to evolve, it holds potential for shaping the future of architectural practice, offering a range of possibilities for creating meaningful and personalised artefacts to enrich interior spaces.

18. Rael and San Fratello, "Printing Architecture: Innovative Recipes for 3D Printing"
19. Sparke, "Nature Inside: Plants and Flowers in the Modern Interior"
20. Drag and Drop, "The Team"
21. Parametric Architecture, "3D-Printing Ceramics 2.0 – Studio Josef Stoger"



Figure 3.1.1 - The "Swilt Cream" vase (left) and the "Ripple Black" vase (right), both designed by Madalin Gheorghe and Dragos Sabareanu of Drag & Drop Design. These vases showcase unique textures and modern aesthetics, combining functionality with artistic expression to create nature-inspired designs.



Figure 3.1.2 - The "Earthlight" lamp (left) and the "Synapse Body" sculpture (right), both designed by Josef Stöger of StögerHaus in 2023. "Earthlight" is a sculptural lamp created in collaboration with Goldenearth Studio, symbolising the intricate relationship between humanity, technology, and nature. "Synapse body" is part of an ongoing exploration of post-tensioned ceramics.

3.2 – ARCHITECTURAL PRINCIPLES OF CERAMIC 3D PRINTED PLANT SYSTEMS

Clay 3D printing offers innovative solutions for indoor plant pottery in the broader realm of plant farming, which bridges natural growth with human interaction and education. Vertical clay 3D printed farming presents a novel approach to plant-centric design by maximising space efficiency and promoting sustainable food production in urban environments. Two case studies, the IAAC Smart City Expo World Congress and Co-Mida's Bio Photovoltaic Vertical Gardens, explore how vertical clay 3D printed farming contributes to plant cultivation and growth-driven design while fostering community engagement and environmental stewardship.

The Institute for Advanced Architecture of Catalonia (IAAC) showcased its vision for the future of urban agriculture through the Smart City Expo World Congress, featuring a vertical clay 3D-printed farming installation (Figure 3.2.1). This innovative project demonstrated the potential of vertical farming to address food security challenges in densely populated cities while minimising land use and environmental impact.[22] IAAC's vertical farming system provided a platform for growing fresh produce by utilising clay as a sustainable and biodegradable material. It was an educational tool for promoting urban farming practices and fostering community resilience.[23]

Co-Mida, a collaborative initiative focused on sustainable food systems, unveiled its Bio Photovoltaic Vertical Gardens as a groundbreaking example of clay 3D printed farming (Figure 3.2.2). This project combined advanced photovoltaic technology with vertical gardening techniques to create self-sustaining ecosystems that harness solar energy for plant growth. By integrating clay 3D printing into the fabrication process, Co-Mida achieved intricate designs that optimise sunlight exposure and water distribution, resulting in higher crop yields and reduced resource consumption. Moreover, the interactive nature of the vertical gardens engages visitors in hands-on learning experiences, highlighting the interconnectedness of technology, nature, and food production.[24]

Vertical clay 3D printed farming offers a multifaceted approach to plant cultivation and growth-driven design, facilitating connections between humans, plants, and the built environment. By reimagining traditional plant-growing practices in vertical spaces, these innovative projects maximise land efficiency and create opportunities for urban dwellers to reconnect with nature and cultivate a deeper appreciation for sustainable food systems. The IAAC Smart City Expo World Congress and Co-Mida's Bio Photovoltaic Vertical Gardens exemplify the transformative potential of vertical clay 3D-printed farming in fostering plant-centric design and sustainable urban agriculture. The potential lends itself to bridging gaps between plant and human scale design, creating dynamic ecosystems that support healthy plant growth while educating and empowering urban communities to embrace more sustainable lifestyles.

22. Despommier, "The Vertical Farm: Feeding the World in the 21st Century"
23. IAAC, "IAAC Vertical Food Farm at the Smart City Expo World Congress"
24. IAAC, "Co-Mida"

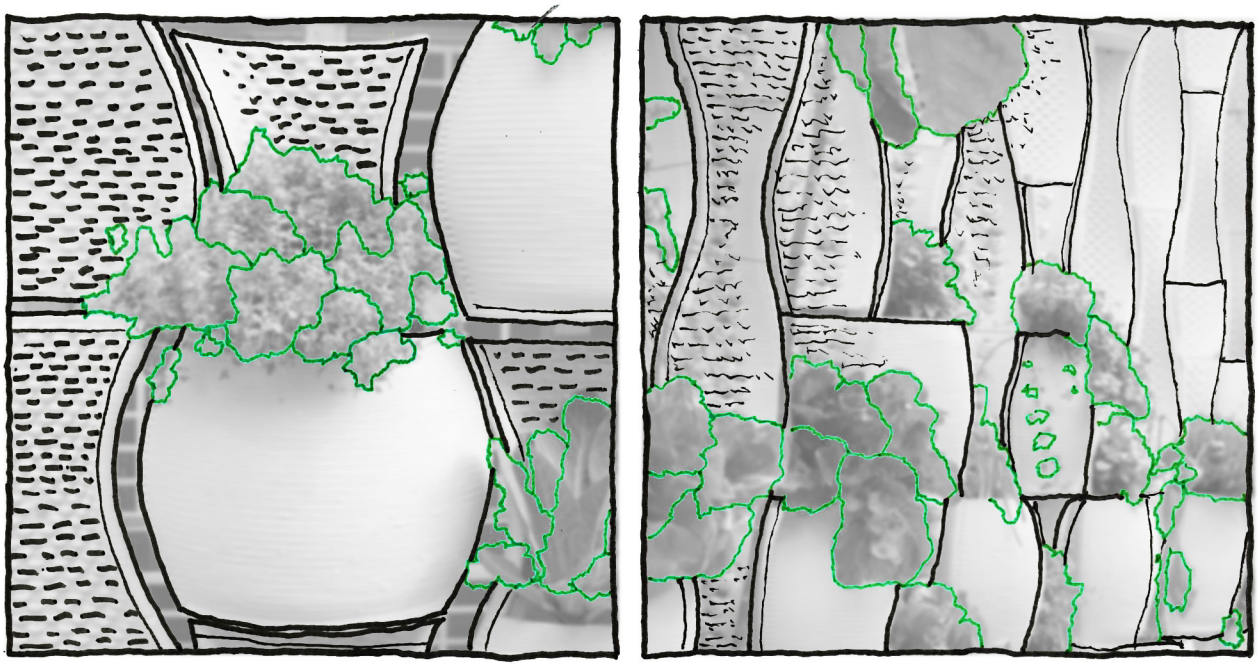


Figure 3.2.1 - The IAAC presented the "Vertical Food Farm" project at the Smart City Expo World Congress in Barcelona, Spain, in the fall of 2019. The project is co-designed with URBiNAT network, Biopolis, CES, Domus Social, Municipality of Porto, IAAC, and primary education public entities. In the spring of 2023, the work was co-implimented in schools located in Porto, Portugal.

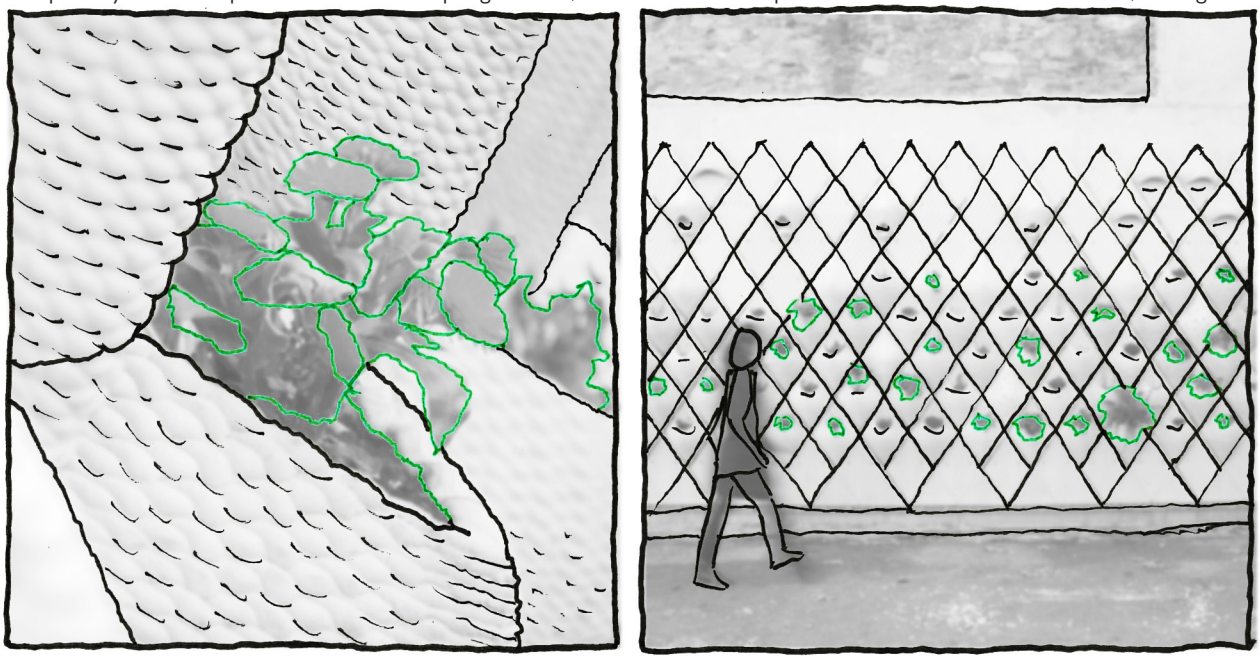


Figure 3.2.2 - Co-Mida's Bio Photovoltaic Vertical Gardens, inaugurated in Barcelona, Spain, on March 5th, 2022, was a winning project of Ciutat Proactiva, 2020. The brief called for urban innovation to face the challenges of urban inclusion and sustainability in the context of COVID-19. The project was a collaboration between IAAC, Sun Sun Love, ConnectHort, and Taula Eix Pere IV.

3.3 – HYBRIDISED CERAMIC 3D PRINTED SYSTEMS

Integrating intricate hybridised systems within clay 3D printing design offers new possibilities for advancing functionality and ease of assembly. Two case studies, Ceralab's Biomic Wall and The Cabin of 3D Printed Curiosities, illustrate the capabilities and relevance of using clay 3D printing in hydroponic systems and ease of assembly design.

Ceralab's Biomic Wall exemplifies the seamless integration of hydroponic systems within clay 3D printing design (Figure 3.3.1). This innovative project combines the benefits of hydroponic cultivation with the structural versatility of clay-based materials, creating a vertical gardening solution that maximises space efficiency and promotes sustainable plant growth. By incorporating hydroponic channels directly into the clay 3D printing process, Ceralab's Biomic Wall enables plants to thrive in nutrient-rich water while minimising water consumption and environmental impact. Moreover, the modular design of the Biomic Wall allows for easy assembly and customisation, making it accessible to a wide range of users seeking to incorporate vertical gardening into their living or working spaces.[25]

The Cabin of 3D Printed Curiosities showcases the intricate design capabilities and ease of assembly afforded by clay 3D printing technology (Figure 3.3.2). Designed as a collaborative project between artists, architects, and engineers, this whimsical structure features many intricate details and functional elements seamlessly integrated into its clay-based framework.[26] From intricate patterns and textures to modular components and built-in fixtures, The Cabin of 3D Printed Curiosities demonstrates the versatility and adaptability of clay 3D printing in realising complex designs with precision and efficiency. Moreover, the ease of assembly inherent in clay 3D printing allows for quick and straightforward construction, enabling users to bring their creative visions to life with minimal effort and resources.[27]

Both the Biomic Wall and the Cabin of 3D Printed Curiosities highlight the beneficial capabilities of clay 3D printing in integrating hybridised systems and promoting ease of assembly. By leveraging the structural and aesthetic qualities of clay-based materials, these projects demonstrate the potential for clay 3D printing to reimagine the fields of hydroponics and assembly design. The two case studies offer design explorations that incorporate responsive ceramic systems that contribute to the overall design efficiency, from the system's assembly to its long-term function.

25. Ceralab, "Biomic Wall: A Ceramic 3D Printed Hydroponic Wall"
26. Emerging Objects, "Cabin of 3D Printed Curiosities"
27. Rael and San Fratello, "Printing Architecture: Innovative Recipes for 3D Printing"

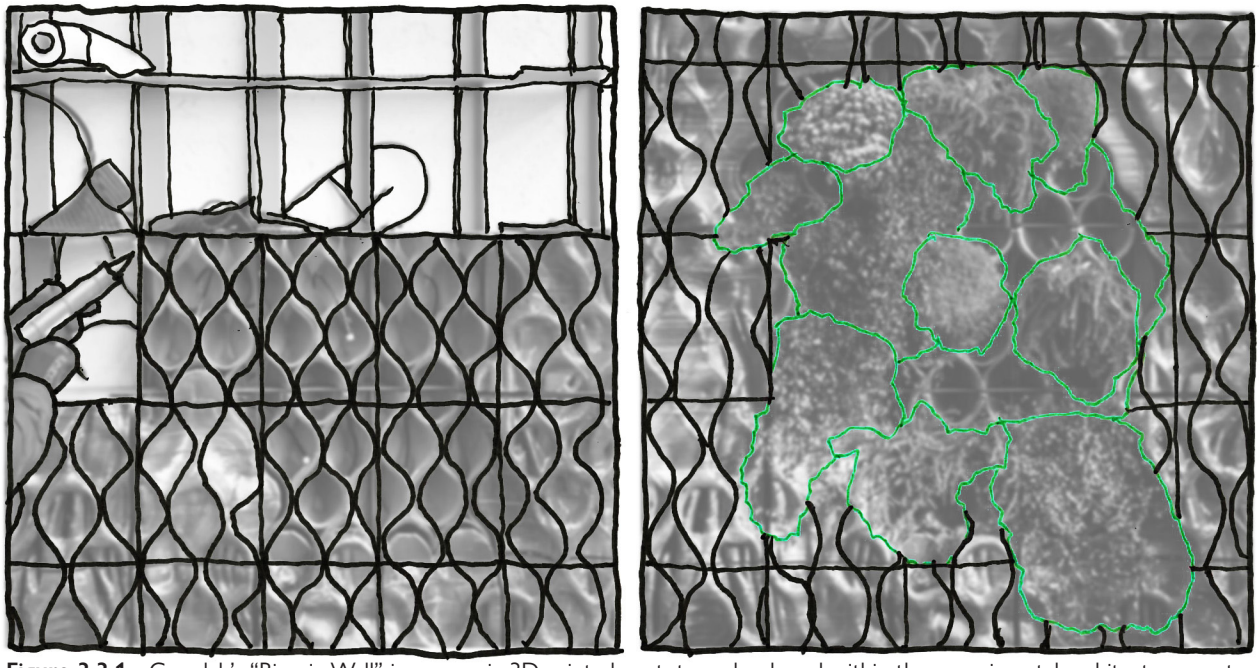


Figure 3.3.1 - Cera-lab's "Biomic Wall" is a ceramic 3D printed prototype developed within the experimental architecture master course at the University of Innsbruck, Austria. The project took place in the winter of 2022 - 2023 to form an urban vertical biotope that acts as a hybrid structure, consisting of a complex multi-part ceramic 3D printed system.



Figure 3.3.2 - Emerging Objects' "The Cabin of 3D Printed Curiosities", led by Ronald Rael & Virginia San Fratello, collaborated with 3D printing designers to demonstrate the architectural potential of additive manufacturing on a building. In Oakland, CA, USA, in 2018, the project was completed in response to the housing emergency in the Bay Area. Photos by Matthew Millman.

CHAPTER 4 – PLANT-CENTRIC ARCHITECTURE PROCESS

4.1 – RESEARCH

4.1.1 – Research Parameters (RP) Overview

The research phase identified design principles, criteria, and priorities for the 1:1 scale plant-centric prototypes as research parameters (RP). Each RP addresses and corresponds to a research objective (RO):

RP1 Clay 3D Printed Plant-growing Vessel and Grow-light Shade: The 3D printed clay vessels must support the plant's typology and were shaped to optimise space and nutrient distribution. The porosity of the clay helped in air exchange and root aeration. The vessels must be designed to support the plants an adequate distance above the nutrient water of the hydroponic system. The plant-centric system's design also includes the grow light shade design, a feature that showcases the system's adaptability. This design incorporates an LED grow light that can be managed to follow lighting schedules. The adjustable light cycle, a key feature, provides the necessary light spectrum for photosynthesis. This adaptability to the plant's light requirements is a significant aspect of the plant-centric system, inspiring confidence in its ability to cater to a variety of plant needs.

RP2 Leafy Green and Herb Plant Typologies: The overall design of the plant-centric architecture prototype must be designed for the plant architecture scale of selected leafy green and herb typology families (Figure 4.1.1.1). These family types exhibit similarities in hydroponic systems. Both families thrive under controlled conditions, showing comparable growth rates due to their short life cycles and high nutrient uptake efficiency. These plants typically achieve similar widths and heights, with most leafy greens and herbs reaching a mature size of 12" - 18" tall and wide, making them well-suited for compact arrangements in hydroponic setups. Their root systems are relatively shallow and fibrous, which adapt well to the deep-water culture (DWC) hydroponic method. Additionally, both plant families require similar lighting conditions, flourishing under 12 - 16 hours of light per day, and benefit from consistent watering schedules. The uniformity in their typological scale allows for effective co-cultivation and maximises space utilisation, ensuring robust and efficient growth yields.

RP3 Adjustable System Design: The suspension system design, a critical component of the plant-centric system, is designed to be suspended, with adjustable features that allow for modification of the distance between the plant and the grow light, maintaining an optimal distance of 12" - 16" to ensure even plant growth. This dynamic system is a testament to the adaptability and effectiveness of the plant-centric system. It ensures optimal light exposure as plants grow and provides versatility in the system's location within an enclosure, emphasising its flexibility and suitability for various plant growth scenarios. This flexibility is not just a feature but a critical factor in ensuring that plants receive the correct amount of light at different growth stages. If the light is within 6" of the plant, it is too close and causes drying and yellowing. If the light is greater than 16" from the plant, it is too far and causes the plant to stretch. This underscores the significance of work in the field of plant-centric system development.



Figure 4.1.1.1 - A matrix of the plants the plant-centric architecture prototypes are designed for. Illustration by Yannik Sigouin.

4.1.2 – Plant System Parameters

Since leafy greens and herbs were selected for the prototype, the design must accommodate shallow root systems and optimise leaf exposure to light. The plant families of leafy greens and herbs typically have modest spatial requirements but benefit significantly from controlled environments that support rapid growth and high yields[28] (Figure 4.1.2.1). These plant families have specific needs that must be considered in the design:

- Nutrient Medium: They require a consistent supply of water and nutrients. Traditional soil can be replaced with hydroponic systems that offer more efficient nutrient delivery.
- Light: These plants need sufficient light, typically in the blue and red spectra, to facilitate photosynthesis.
- Air Circulation: Proper airflow prevents diseases and supports transpiration.
- Space: Adequate spacing prevents overcrowding and ensures each plant receives ample light and air.

4.1.3 – Hydroponic System Parameters

Hydroponic systems are commonly used in indoor farming, optimising plant growth due to the system's focus on plant vitality. The DWC hydroponic Kratky system presents a sustainable alternative to soil-based growing (Figure 4.1.3.1). It involves suspending plant roots in a nutrient-rich water solution, allowing for direct nutrient absorption.[29] Key benefits of this system include:

- Efficiency: Direct nutrient delivery can lead to faster growth rates.
- Water Conservation: Uses less water than traditional soil-based methods.
- Minimal Maintenance: Once set up, it requires less frequent monitoring.

4.1.4 – Ceramic 3D Printed System Parameters

The Kratky system offers a desirable means of designing a plant-centric system. These systems often lack the incorporation of architecture to help elevate the functionality and overall aesthetics. The design implementation of clay 3D printing offers advantages to leverage plant-centric design:

- Porosity: Allows for breathability and moisture regulation.
- Customisation: Enables precise and intricate fabrication tailored to plant needs and design aesthetics.
- Sustainability: Clay is a natural, eco-friendly material.

28. Flo, "Best Plants for Deep Water Culture: Enhancing Your Hydroponic Garden - Hydroponics List"
29. Kratky, "Three Non-Circulating Hydroponic Methods for Growing Lettuce"

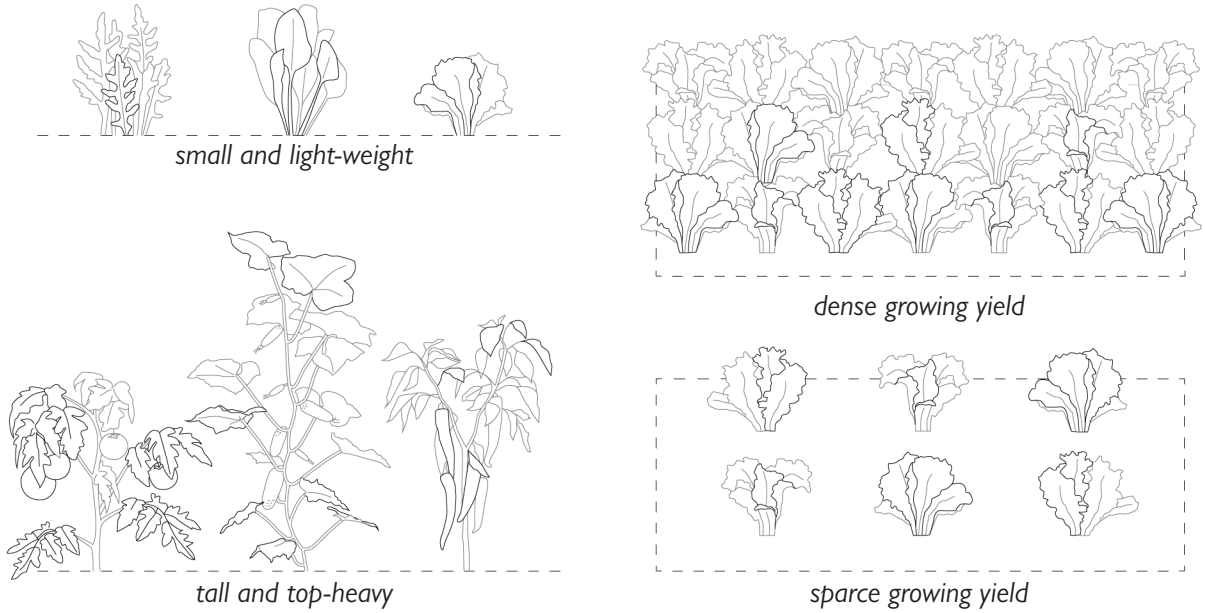


Figure 4.1.2.1 - Important qualifications for the plant typologies. The prototypes look to design for small and lightweight crop types to minimise top-heavy growing issues (left). The prototype designs also look to facilitate denser growing yields, maximising crop potential (right). Diagram by Yannik Sigouin.

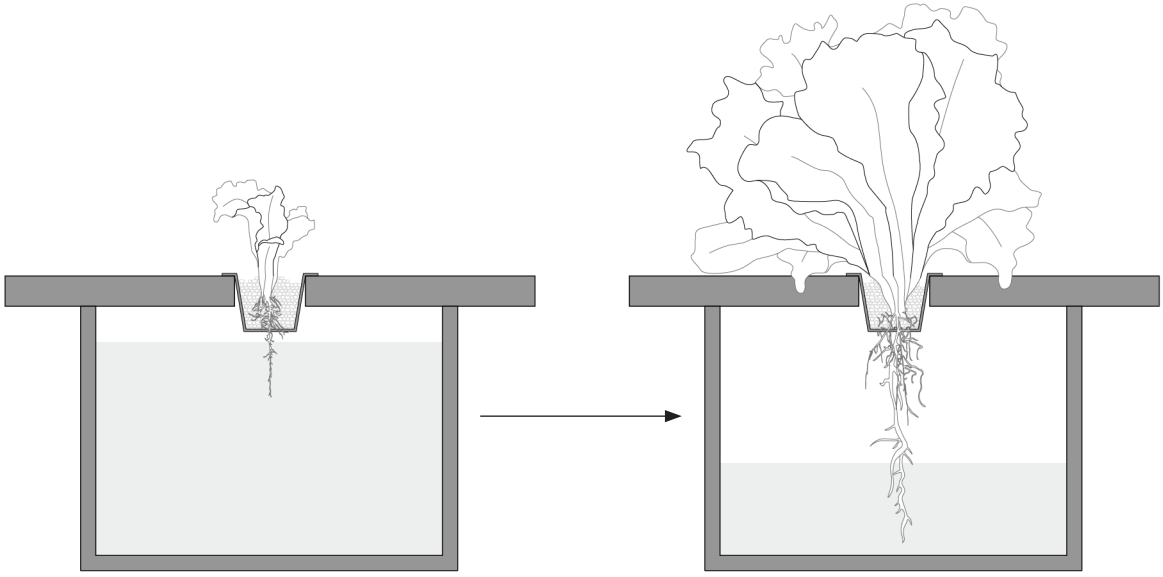


Figure 4.1.3.1 - Diagram of the Kratky method, a popular passive hydroponic technique for growing plants among home growers due to its ability to be carried out on smaller scales. The method is named after Bernard Kratky, a researcher at the University of Hawaii, who first proposed the method in the journal Acta Horiculturae in 2009. Diagram by Yannik Sigouin.

4.1.5 – Grow Light System Parameters

Grow lights are essential in the use of indoor farming systems as interior spaces hinder the amount of natural daylight plants require to thrive. Incorporating a light fixture within the system is mandatory. Thus, it is essential to study how clay fabrication can manipulate and enhance light. To understand methods for creating 3D-printed ceramic artefacts that study lighting effects, the work by Isabel Ochoa and James Clarke-Hicks (OCHWorks) is reviewed (Figure 4.1.5.1). Their work demonstrates how material deformation can alter lighting effects in 3D-printed ceramics and identifies methods for creating apertures.[30] The result is to produce a grow light component that focusses on the vitality of the plant subject, while also enhancing the overall aesthetic of the system. The methods for creating apertures include:

- Overhangs: Alternates print layers to create unsupported areas of the tool path that produce small gaps in the printed artefact.
- Light Shelves: Builds on the overhang method by stacking and offsetting multiple layers of unsupported overhangs to create an angled shelf.
- Light Scoops: Undulate tool paths that are offset from one another to create vertical channels through the printed artefact.

30. Ochoa and Clarke-Hicks, "Grading Light: Utilizing Plastic Deformation to Functionally Grade Ceramic Light Screens"



Figure 4.1.5.1 - The "OIL LAMP 02" light fixture (top) combines methods of overhangs and light shelves to produce light apertures, while the "TOAD 02" light fixture (bottom) exemplifies the method of creating light scoop apertures. Both pieces were designed and fabricated by Isabel Ochoa & James Clarke-Hicks of OCHWorks.

4.2 – SCHEMATIC DESIGN

4.2.1 – Plant Vessels

The vessel system needs to be compartmentalised so that each plant has its own vessel to grow in. This prevents slower-growing plants from eventually having their roots suspended above the water level as the faster-growing plants take up the nutrient solution (Figure 4.2.1.1). Additionally, the vessels' interior volume should contain between 0.5 and 1L of water to allow small to medium-sized plants enough root space to develop into full maturity.

4.2.2 – Lighting System

The grow lights used in the proposed plant-centric architecture must serve two purposes: they must provide sufficient energy for the plants to grow and offer a pleasant ambient light to the interior space. Therefore, it is necessary to select lights suitable for plant growth and safe for daily interior use. The Sunblaster CFL bulb and the Necgemlex Smart LED are appropriate bulbs for residential and agricultural use. These bulbs were purchased to conduct lighting tests and assess the most suitable light for indoor plant-growing systems.

The Sunblaster CFL bulb is at 6400K, akin to cool, natural daylight and the ideal colour range for vegetative plant growth. It was purchased in two sizes, 26 Watt and 13 Watt. Preliminary lighting tests revealed that this bulb is very bright to the eye and becomes hot when used for long periods of time.

The Necgemlex Smart LED grow light has a warmer colour temperature of 4500K, suitable for all stages of plant growth, from flowering to vegetative. This is a 9-watt bulb that features three modes of brightness. This light is more comfortable to the eye than the Sunblaster CFL bulb, and when used for long periods, it becomes warm but not hot to the touch.

Following the preliminary lighting tests, it was determined that the Necgemlex Smart LED grow light was the most comfortable lighting option. The colour temperature is warmer and more conducive to use in interior spaces. The brightness is also more comfortable to the eye and can be adjusted as required. Lastly, this bulb does not get hot to the touch, which is necessary as it will be near the system's suspension elements and plant foliage.

In the design of the proposed plant-centric architecture systems, one light bulb was positioned above the plants to give them a direct energy source to grow. Light shades will direct the light towards the plants and prevent harsh, unfiltered light from reaching the interior space. Lastly, the distance between the plant and the grow light is essential for healthy plant growth. The Necgemlex Smart LED bulb recommends a 12" - 16" distance between the plant and the light bulb. If the plant is too close to the bulb, its leaves may burn. If it is too far from the bulb, it will stretch to grow in the direction of the light and develop long stems and few leaves (Figure 4.2.2.1). The plant will continually grow and change in the system. Therefore, the position of the plant growing vessels must be adjustable relative to the position of the light to allow for the ideal distance of 12" - 16" to be maintained.

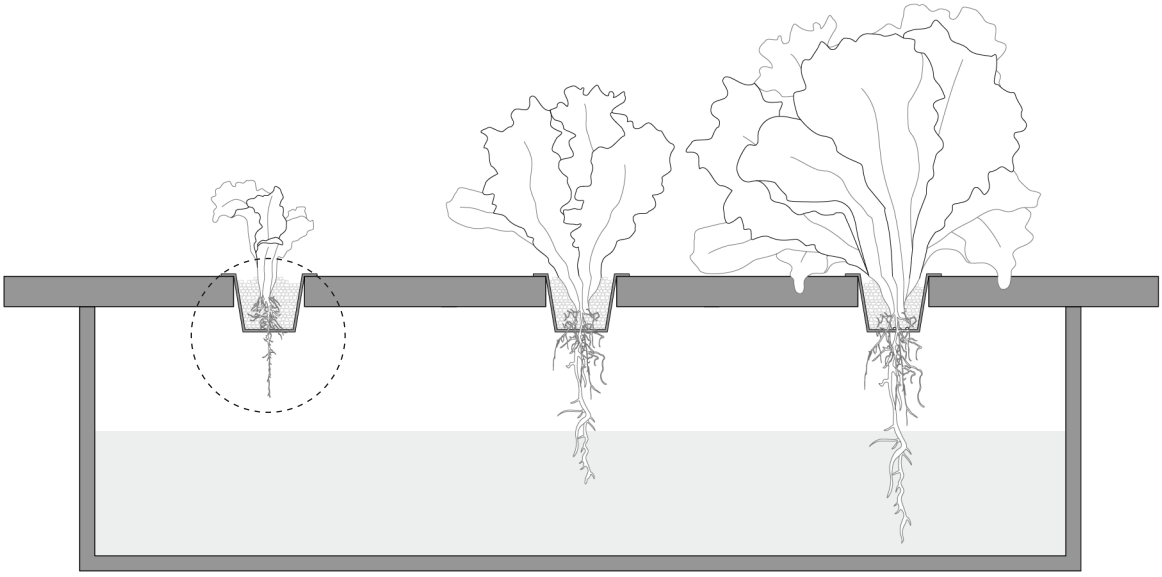


Figure 4.2.1.1 - The plant growing vessels should be compartmentalised.
Diagram by Yannik Sigouin.

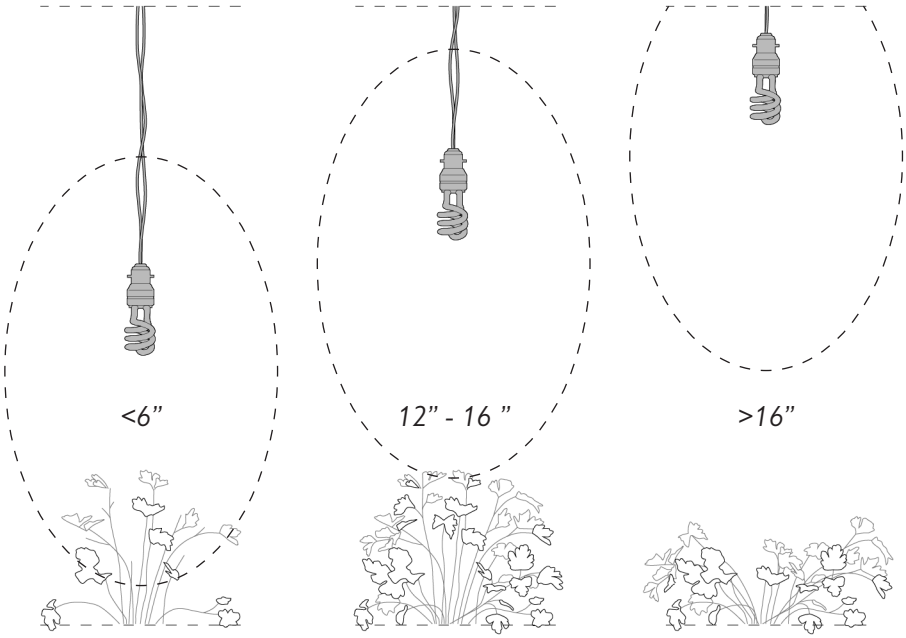


Figure 4.2.2.1 - Diagram showing plant growth in relation to the position of the grow light.
Diagram by Yannik Sigouin.

4.2.3 – Support & Suspension System

Structural support components are required to connect elements of the light fixture to the existing indoor structure. The structural design must allow the plant-growing vessels to move and maintain the recommended distance between the plants and the grow lights. The plant-growing vessels should also be able to detach from the structural system for cleaning and maintenance (Figure 4.2.3.1 - 4.2.3.5).

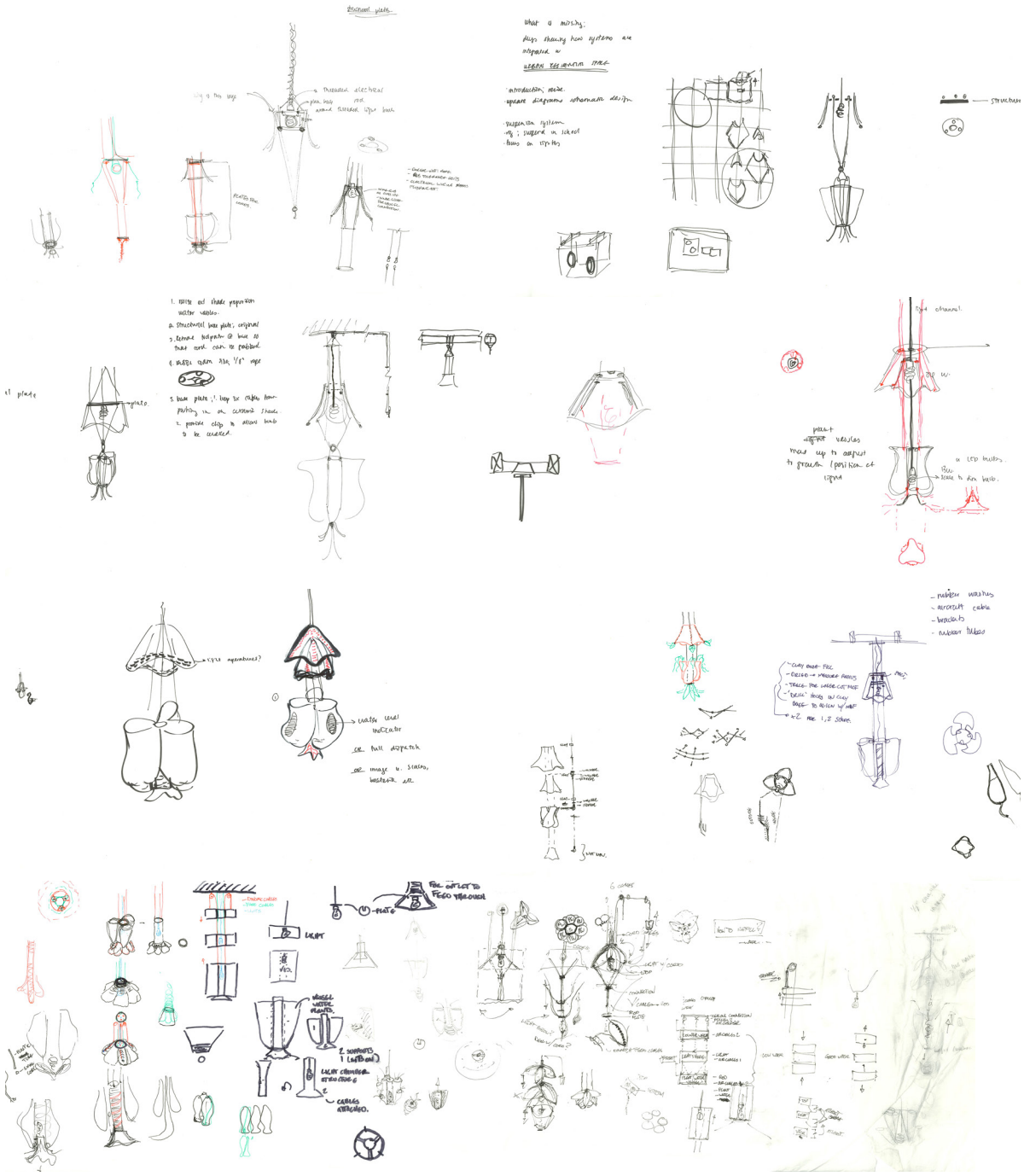


Figure 4.2.3.1 - Scanned images of the trace paper that was sketched on throughout the whole design process. Sketches by author Yannik Sigouin & Taylor Murray.

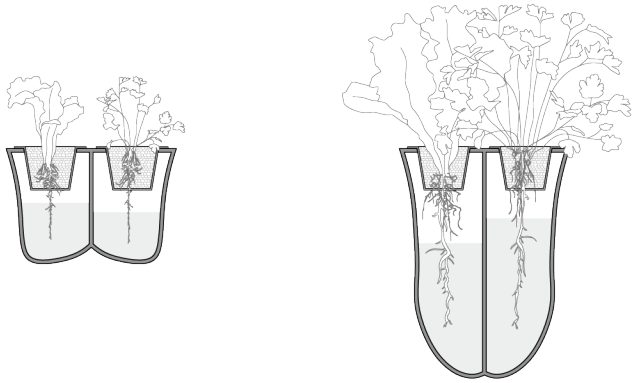


Figure 4.2.3.2 - The plant-growing vessels will be compartmentalised (left). The interior volume of the plant vessels will be able to contain between 0.5L - 1.0L of water to allow plants to grow to full maturity (right).
Diagram by Yannik Sigouin.

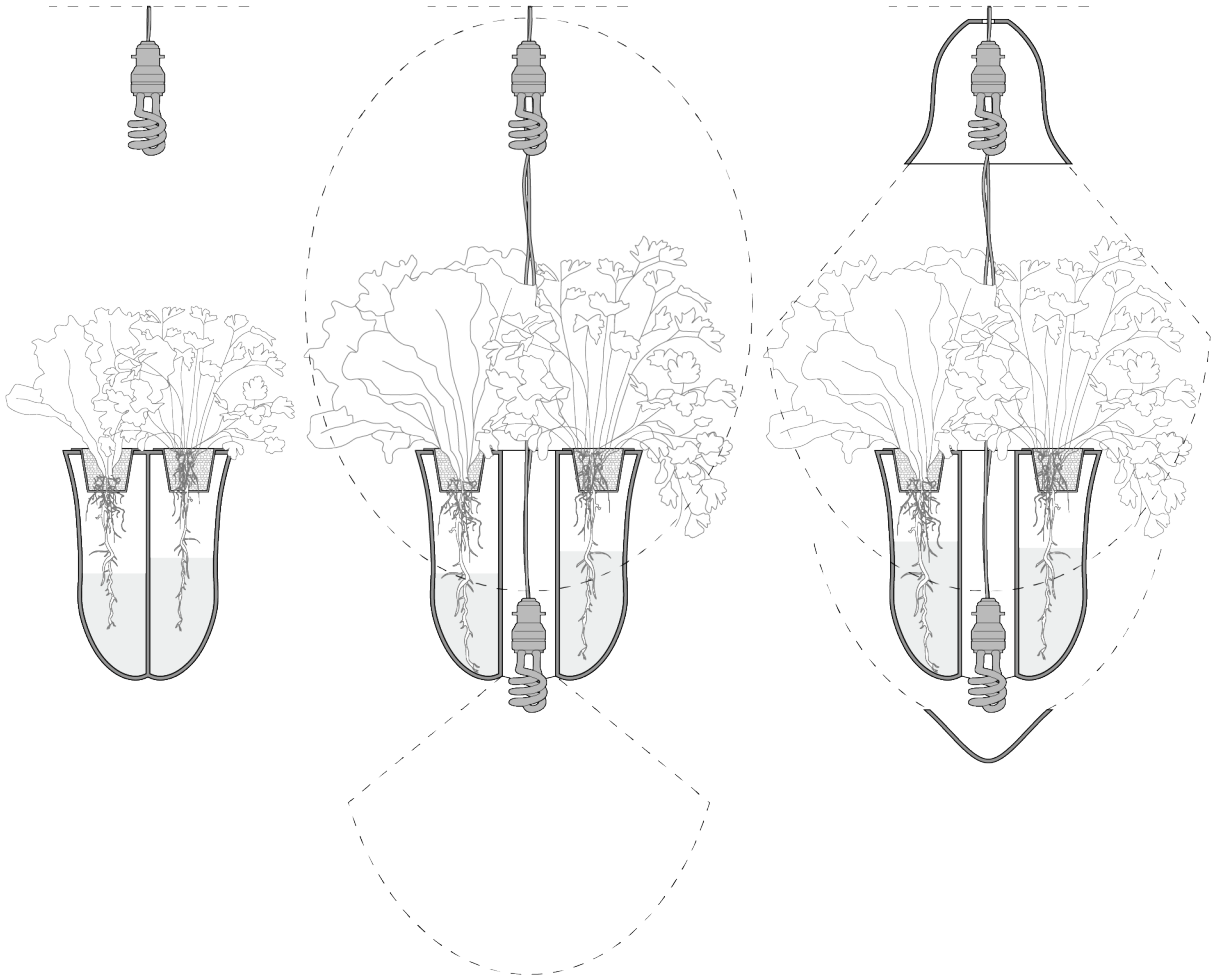


Figure 4.2.3.3 - A grow-light bulb will be positioned above the plants to directly provide them with energy (left). A second grow-light bulb may be positioned below the plants to encourage them to grow fully around the system (middle). Light shades above and below will be used to control the direction and intensity of the light (right).
Diagram by Yannik Sigouin.

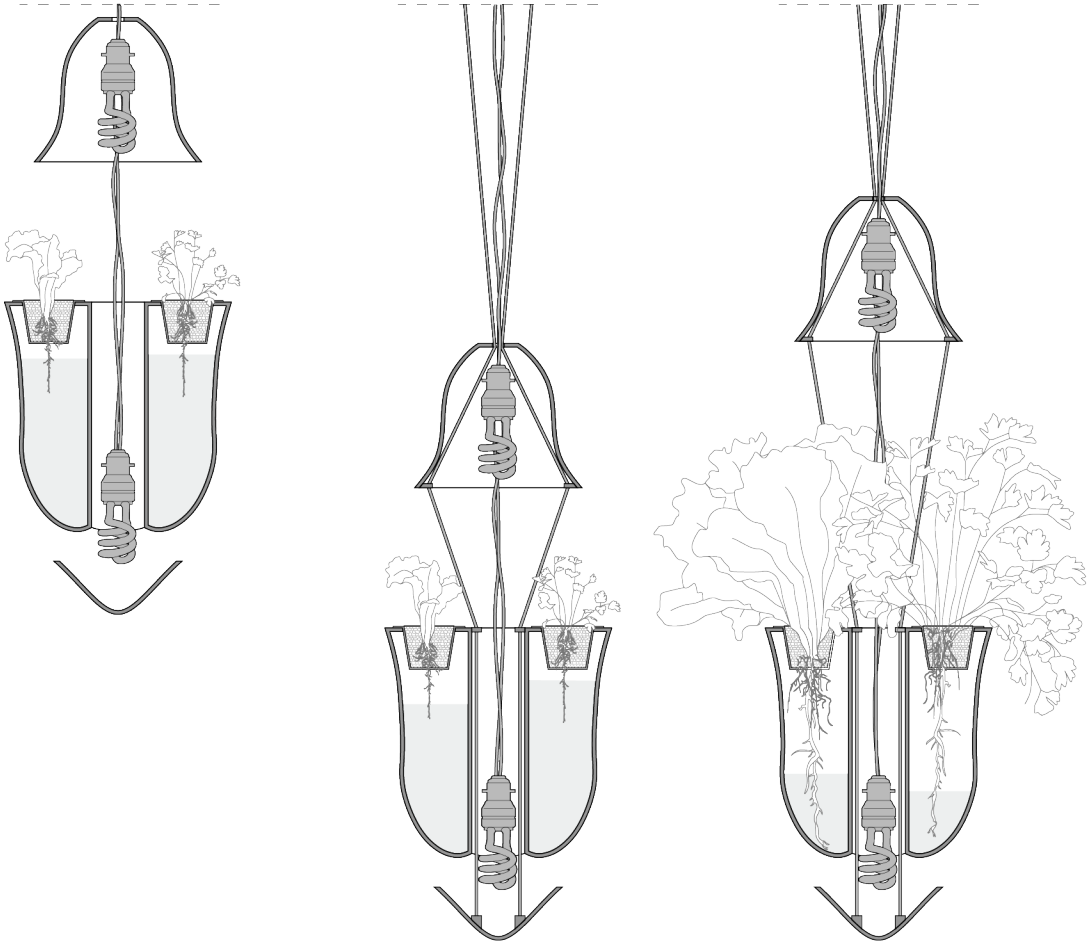


Figure 4.2.3.4 - The distance between the grow-light bulb and the plants will be adjustable to accommodate different stages of plant growth (left). Components of the system will be connected to one another (middle). The support structure will allow for the position of the plant-growing vessels to be adjusted (right).
Diagram by Yannik Sigouin.

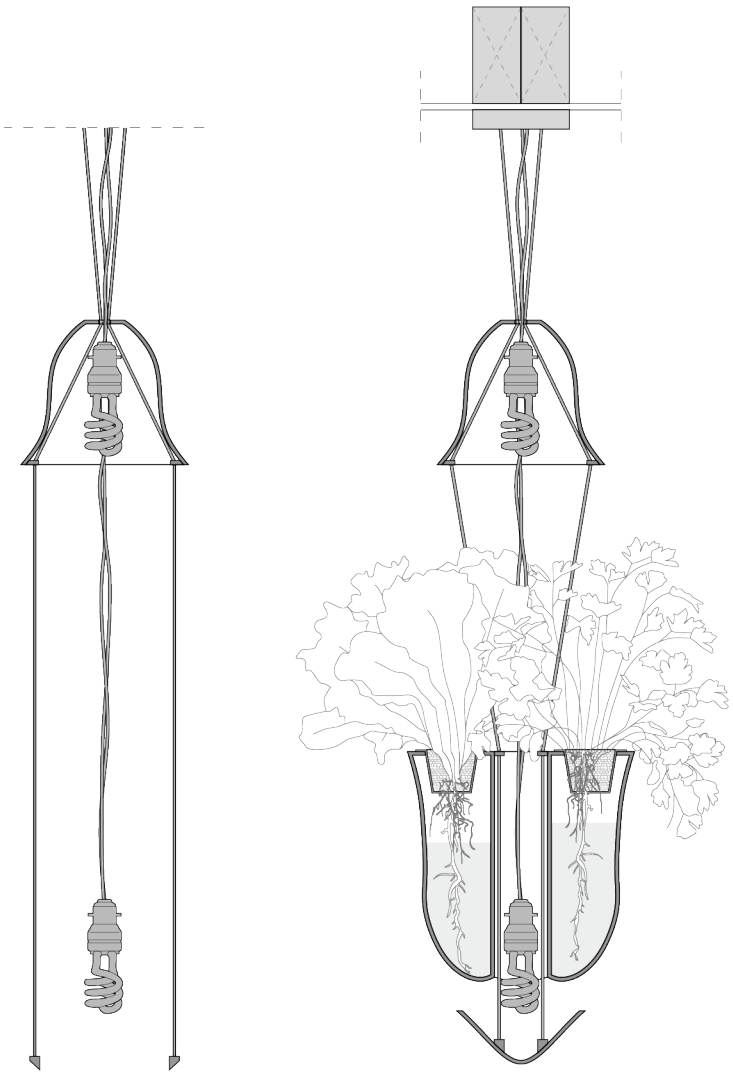


Figure 4.2.3.5 - The plant-growing vessels will be able to detach from the system to allow for cleaning and maintenance (left). The system will connect to existing indoor structures (right).
Diagram by Yannik Sigouin.

4.3 – DESIGN DEVELOPMENT

The design development phase investigated the massing, aesthetic, and structural considerations for the plant-growing systems. The process was broken down into multiple iterations to allow for the ceramic prototypes to be developed in detail. All components were fabricated using a 3mm nozzle and a 2mm layer height. Test prints were created using the Scara 3D printer in the first iteration. Though the Scara produces less precise prints than the Lutum, it was used for its ability to develop rapid prototypes at 0.75:1 scale that allowed for print variables such as tool path, print orientation, g-code production, massing, and proportion to be assessed. Tested prints were created at 1:1 size in the second iteration using the Scara and Lutum printers. The precision of the Lutum 3D printer was used to explore aesthetic details such as surface texture and lighting quality. It also allowed the structural system to be accurately integrated with the ceramic components. Chapter 4.4 pertains to the first prototype phase, where the development of the massing and proportional relationships for each component are explored at 0.75:1. Continuing from the first prototype phase, chapter 4.5 reconsidered unsuccessful design intentions and revised accordingly at 1:1.



Figure 4.3.1 - The Scara V4 clay 3D printer (left) and the Lutum 4.6 clay 3D printer (right).
Photos by Yannik Sigouin.

4.4 – PROTOTYPE PHASE 1

4.4.1 – Overview

Phase 1 was intended to develop the massing and proportional relationships for each component, including the light shade above the system, plant-growing vessels, and the light shade below the system (Figure 4.4.1.1). There are two grow lights, one in the upper light shade to project lights down to the plants and one in an open channel in the plant growing vessels. This light reflects off the lower light shade to project light at the plants. An iterative printing process was used to determine how each proposed component massing was best achieved using the capabilities of the clay 3D printer. Structural connections were integrated with each component to allow them to be connected and suspended from an existing structure. Lastly, aesthetic considerations were established in this stage, first by creating an attractive quality to the underside of each component, as the suspended system will be primarily viewed from below. Then, each component was designed to be dynamic, reflecting the system's continually growing and changing plant life. The design development for each component can be assessed using the following categories: massing, print orientation and base condition, structural connections, and dynamic quality.

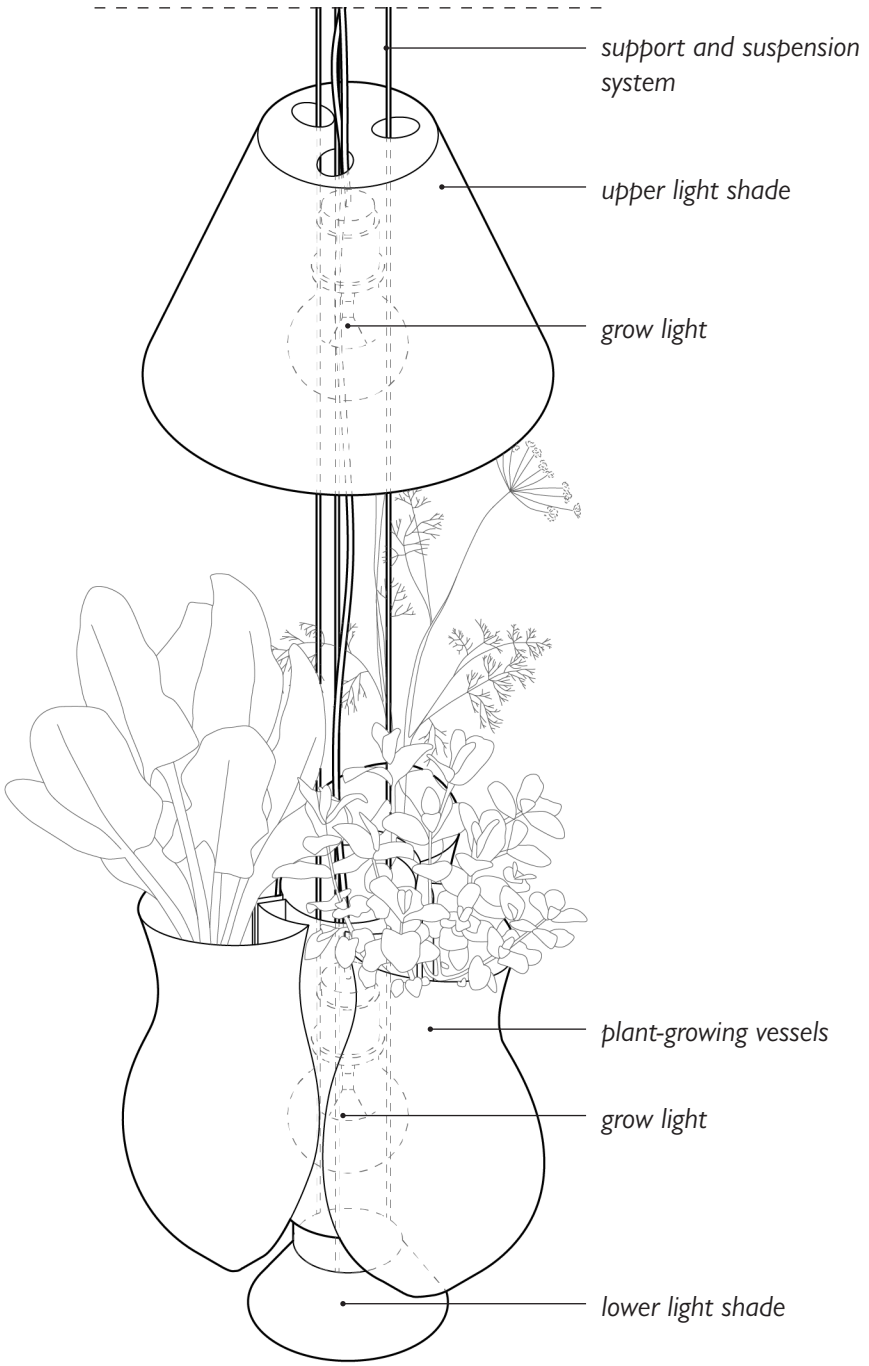


Figure 4.4.1.1 - Prototype phase 1 concept overview for the proposed plant-centric architecture. Diagram by Yannik Sigouin

4.4.2 – Vessels

Massing

The massing for the plant-growing element consists of three vessels arranged around a circular channel. The circular channel is required to allow structural and electrical cables to run through the system. This component was initially printed from bottom to top with a flat base.

Print Orientation & Base Condition

To create visual interest on the underside of the plant-growing vessels, this component was revised to be printed upside-down to allow the base to end in a non-planar geometry. Print path layers offset at a 45° angle to gradually close in the base. The 45° angle was chosen as it is the lowest allowable angle that prevents the tool path from delaminating from itself or buckling in the centre while using a 3 mm nozzle and 2 mm layer height. It is necessary for the tool path to fully close as the plant vessels are required to be water-tight (Figure 4.4.2.1).

Structural Connections

Three structural loops were positioned between the plant-growing vessels to create a point of attachment for cables. These cables provided appropriate support to the system and allowed the fixture to be levelled when suspended.

Dynamic Quality

To create the appearance of movement, the vessels were rotated around the circular channel. The angle at which the vessels rotate around the channel was tested iteratively, using 30°, 45°, and 60° increments. Ultimately, the 60° rotation was chosen, allowing each vessel's top to rotate enough to overlap with the adjacent vessel when viewed in plan (Figure 4.4.2.1). This creates a whole appearance and provides depth when viewing the component from below. Initial experiments in creating texture were achieved by offsetting toolpath points to enhance the surface quality (Figure 4.4.2.2).

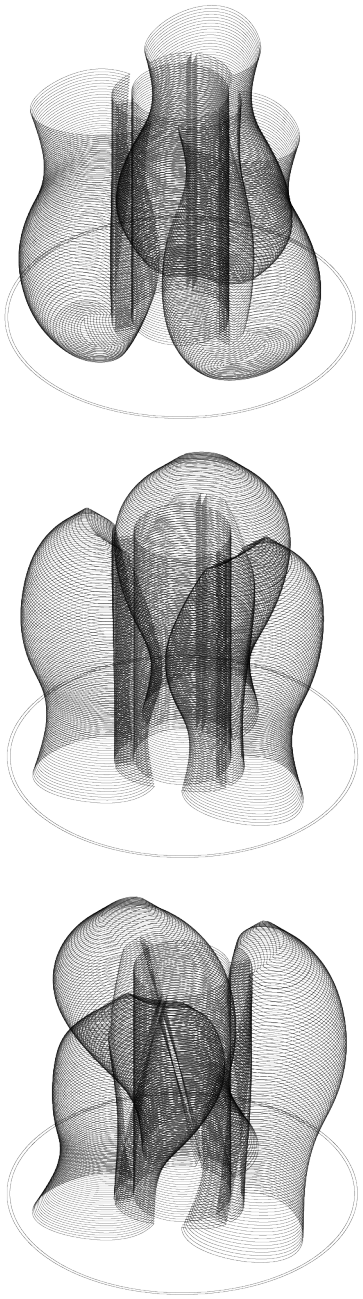


Figure 4.4.2.1 - Plant-growing vessels were printed from bottom-to-top with a flat base (top), then from top-to-bottom to create a curved base (middle). Plant vessels were rotated 60° around the circular channel (bottom).
Diagram by Yannik Sigouin.

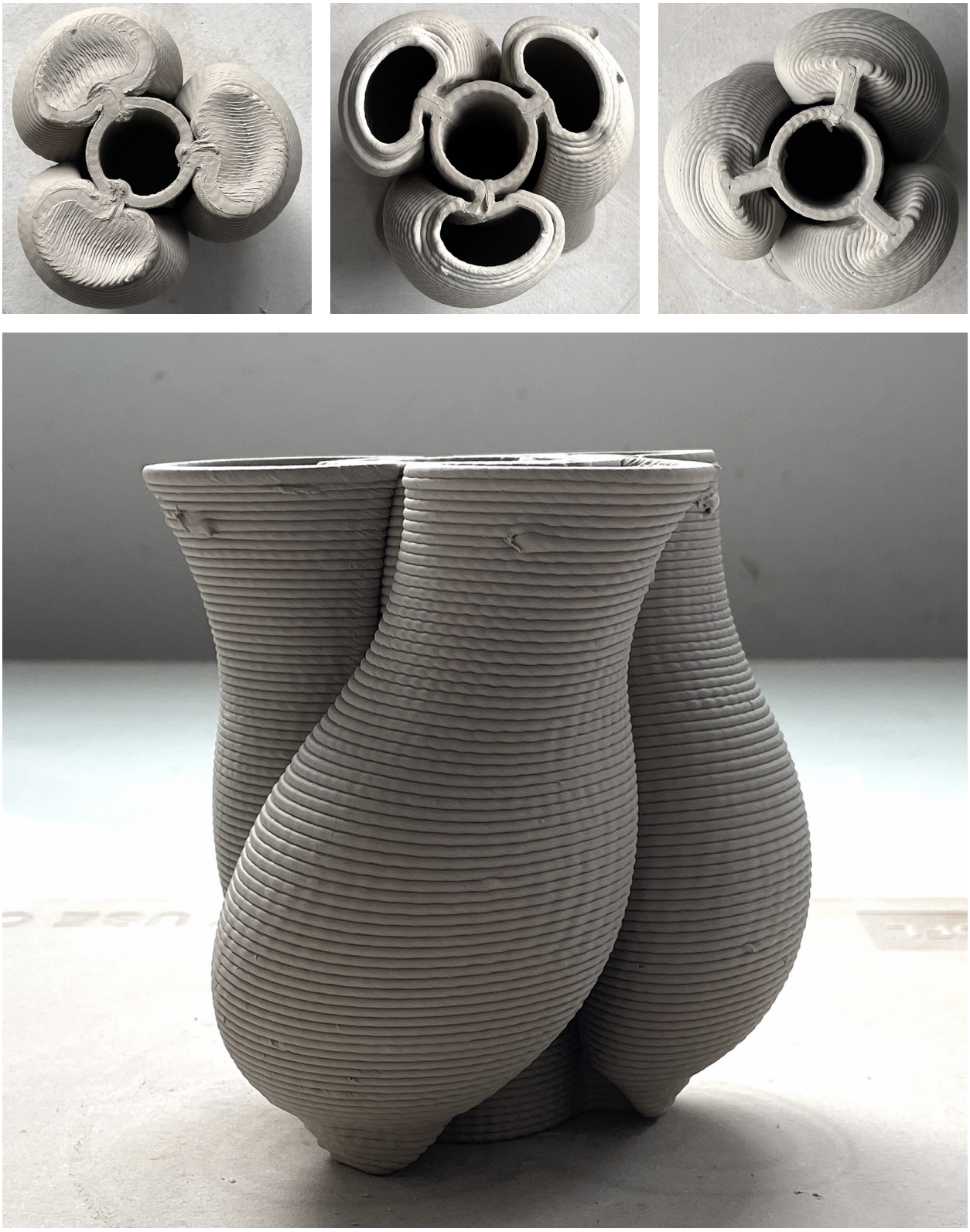


Figure 4.4.2.2 - Comparison between the appearance of the flat base, a delaminated base, and a laminated, curved base (top). Front view of the plant-growing component (bottom).
Photos by author Yannik Sigouin and Taylor Murray.

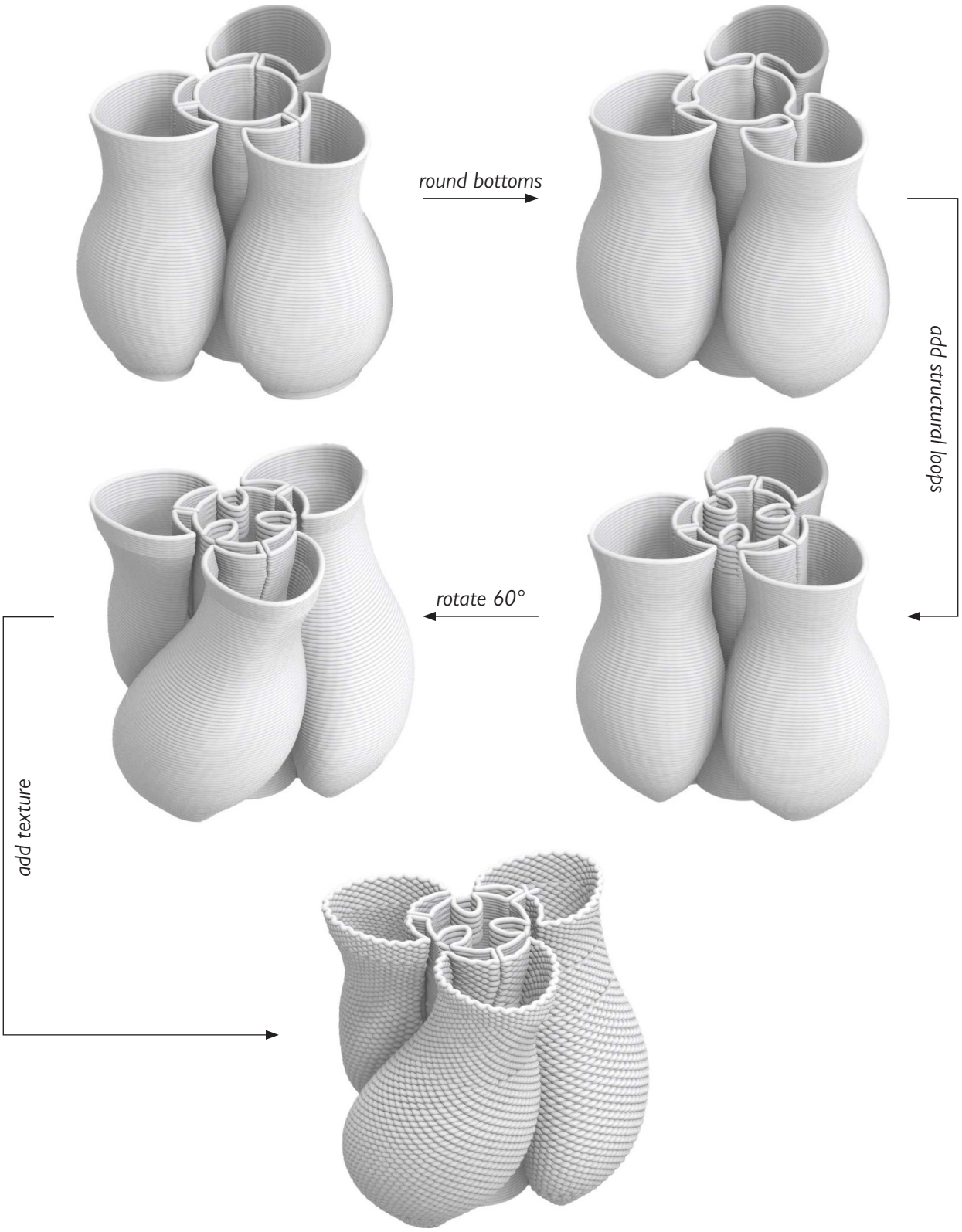


Figure 4.4.2.3 - Summary of plant-growing vessel design progression.
Diagram by Yannik Sigouin

4.4.3 – Upper Light Shades

Massing

The massing began with a narrow cone shape at the base to align with the top of the grow light and broad at the top to direct the light down towards the plants.

Print Orientation & Base Condition

The narrow end of the upper shade required a closed base to hold the grow light in place. This was created by printing two layers flat against the print bed (Figure 4.4.3.1).

Structural Connections

Three structural openings were created in the base plate, aligning with the structural loops in the plant-growing vessels below. These openings provide a point of attachment for cables.

Dynamic Quality

To create the appearance of movement, the edge condition of the light shade ends in a waving curve created using isocurves. Isocurves move non-uniformly in the z-axis to create an undulating line. In this instance, it was used to develop three undulations aligned with the placement of the three plant-growing vessels below.

To create the waving curve, the printer would quickly step up in the z-axis at the high points and then firmly compress down at the low points. This dramatic difference in movement created structural instability across the print, which would lead to immediate collapse or eventual cracking. To accommodate this, structural ribs were added at each curve's high and low points to provide rigidity. This was a successful strategy to prevent distortion and print failure (Figure 4.4.3.3).

Lastly, to further create the appearance of movement, an additional light shade was designed to be nested inside the outermost shade. The smaller, nested shade has the same proportions as the more oversized shade but is rotated 30° so that the high points on the edge of the small shade are aligned with the low points on the edge of the large shade. The same three structural loops are created at the base of the nested shade and are aligned to the three openings on the large shade. The effect of the two nested shades together creates depth (Figure 4.4.3.3).



Figure 4.4.3.1 - A cone shape with a closed base is created (top). A waving curve is used at the opposite end of the cone to create the appearance of movement (middle). An additional light shade is designed to nest inside the outermost shade (bottom). Diagram by Yannik Sigouin.



Figure 4.4.3.2 - The base is printed flat against the print bed with three structural openings. A print that experienced collapse due to changes in z-height remains intact on the right side where the structural seam is located (top). A small shade nests inside the exterior shade and houses the light (bottom). Photos by author Yannik Sigouin and Taylor Murray.



Figure 4.4.3.3 - Summary of light shade design progression.
Diagram by Yannik Sigouin.

4.4.4 – Lower Shades

Massing

The massing began with a cone shape, with a narrow base to fit within the circular channel of the plant-growing vessels above. The opposite end of the cone widens to create a surface for the channelled light above the system to reflect off and direct it up towards the plants.

Print Orientation & Base Condition

The narrow end of the curve was printed against the print bed to provide a flat surface that interfaces with the circular channel in the plant-growing component. This process was the same as the upper light shades.

Structural Connections

Three structural loops are created to align with the loops in the plant growing vessels and the upper light shades.

Dynamic Quality

Waving curves are used to provide a sense of movement across the top edge of the shade and to visually unite the appearance of the lower light shade with the two upper light shades (Figure 4.4.4.1).



Figure 4.4.4.1 - Three structural openings are created at the base. The three light shades used in the system have similar forms but different scales. The components are designed to nest within each other.
Photos by author Yannik Sigouin and Taylor Murray.

4.4.5 – Assembly

Three pieces of aircraft cable were cut into 4' lengths to assemble the system. A vinyl washer and crimping sleeve were threaded onto each piece of aircraft cable and aligned to the structural loops on each ceramic component. The sleeve was crimped once in the correct position, and the aircraft cable was threaded through the ceramic loops. The vinyl washers held the crimping sleeves in place under the structural loop and prevented the edges of the aluminium sleeves from scraping against the ceramic structure. This process was repeated for each of the pieces in the system, starting with the plant growing vessels (1), followed by the interior light shade (2), exterior light shade (3), and lower shade (4) (Figure 4.4.5.1). Care was taken to ensure each component was level before moving on to the next piece. At the bottom end of the aircraft cable, any length left underneath the lower light shade was clipped off. The extra length was finished in a loop using a wire cable-clip at the cable's top end (5). This loop was suspended from an L bracket for installation at the Canadian Clay and Glass Gallery in Waterloo, Ontario, Canada, as part of the Material Syntax exhibition, February 6th to April 7th, 2024 (Figure 4.4.5.2 - 4.4.5.3).

This method of structural assembly posed issues when installing the electrical system. The distance between the three aircraft cables was not significant enough to accommodate the grow light, which prevented the light from being installed in the system. Further, the absence of a central opening through the base of the exterior light shade required that the electrical cables run through the structural openings at the side of the base, which prevented the grow light from being level.

Lastly, the use of crimping sleeves caused all connections in the system to be fixed. This prevented the distance of the plant growing vessels from being adjusted relative to the grow light as the plants grew in the system. It also prevented this component from being able to be removed for cleaning and maintenance. Therefore, future iterations of this system will need to reconsider the structural materials and design to install the grow light properly and to create non-fixed and adjustable connections.

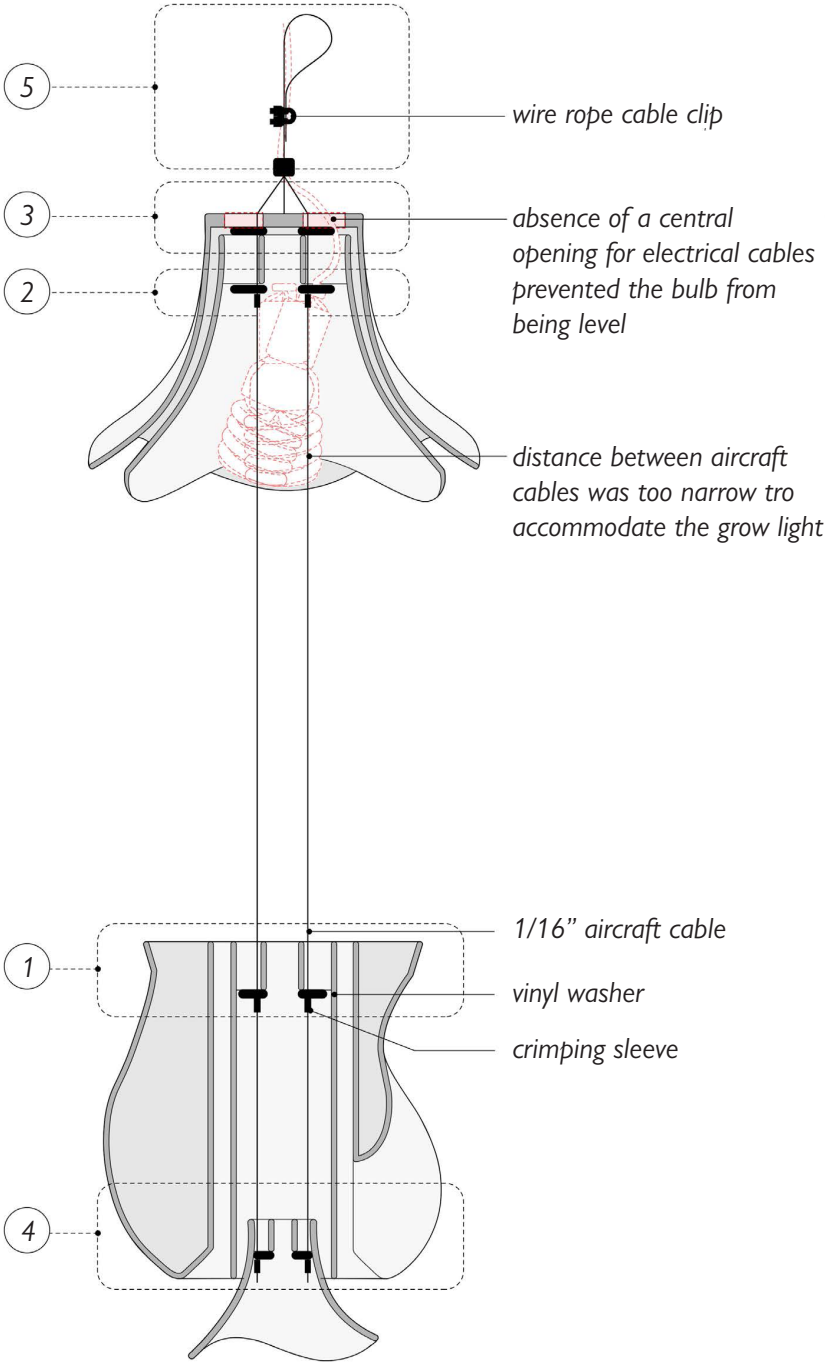


Figure 4.4.5.1 - Diagram showing the structural system for the finished installation at the Canadian Clay and Glass Gallery. Diagram by Taylor Murray.



Figure 4.4.5.2 - Finished installation at the Canadian Clay and Glass Gallery in Waterloo, Canada, as part of the Material Syntax exhibition, February 6th to April 7th, 2024.
Photo by Taylor Murray

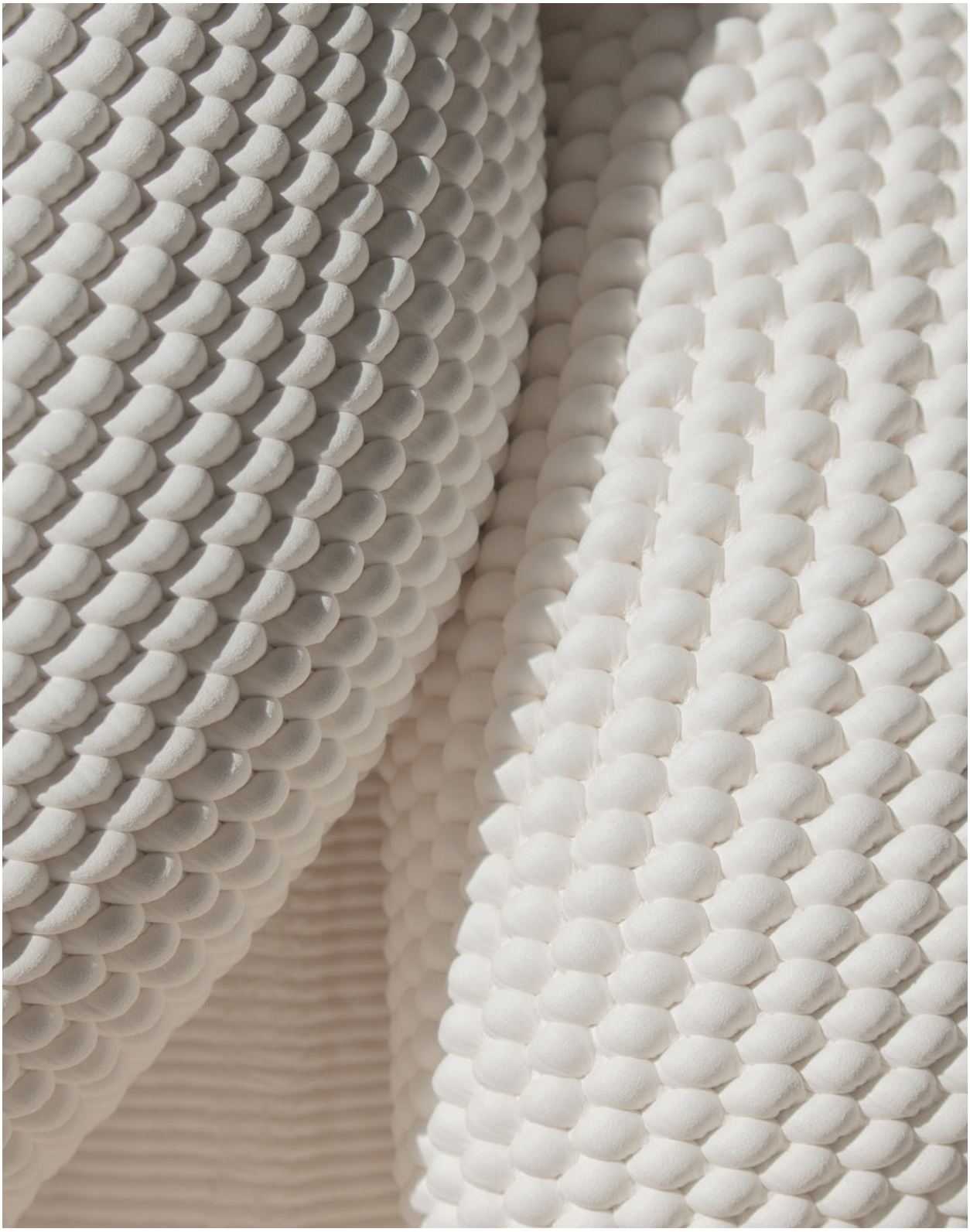


Figure 4.4.5.3 - Texture on plant-growing component.
Photo by Yannik Sigouin.

4.5 – PROTOTYPE PHASE 2

4.5.1 – Overview

The second prototype uses the Scara and Lutum printers to develop ceramic components at a 1:1 scale. The amount of clay that can fit in the extruder tube for the Scara is 3600 cc, and for the Lutum is 1400 cc. This was a limiting factor in scaling up the size of the pieces. All components printed in the second iteration were scaled up to be 25% larger than the geometries created in the first iteration. This size change increased the water in the plant-growing vessels from 0.4 L to 0.5 L. It was impossible to increase the size of the plant-growing vessels by more than 25%, as it would require more than 3600 ccs of clay to produce the component at this scale. The light shades were created using the Lutum printer, as they needed less than 1400 cc of clay and benefited from high detail resolution.

This phase began by reconsidering the design and material choice for the structural system. This was required to allow for the proper installation of the grow light and to create non-fixed connections between components. Instead of continuing to use aircraft cable for the suspension system, ¼" braided rope was substituted. The intention is to use the flexibility of the braided rope to weave the structural system into the ceramic components while creating points of connection that are not permanently fixed. This will allow for pieces of the system to be adjusted or removed as required. It will also allow for the structural system to be tied into the outer edges of the ceramic pieces, preventing the structure from running directly through the system's centre, where clear space for the grow light is required.

The revised concept for the structural system is separated into two parts. The first part is the upper light shades and the grow light. The exterior light shade will be solid and able to move up and down relative to the interior light shade. In contrast, the interior shade will be perforated and have a fixed position in the system. This allows light emitted from the grow light to be controlled and adjusted. The second part of the system is the plant-growing vessels and lower light shade. The position of the plant vessels can be adjusted by moving the location of the knotted connection under the lower light shade. By undoing the knot, the plant-growing component can be removed from the system for cleaning and maintenance. The central channel of the plant-growing system provides a place for the braided rope to run through and offers an adjustable system from within (Figure 4.5.1.1).

Unlike the first prototype phase, which was primarily made digitally using the modelling software Rhinoceros 3D, the second concept prioritised parametric 3D modelling of the system using Grasshopper scripting. This allowed for rapid mass iterations and a more precise means of designing the system's components.

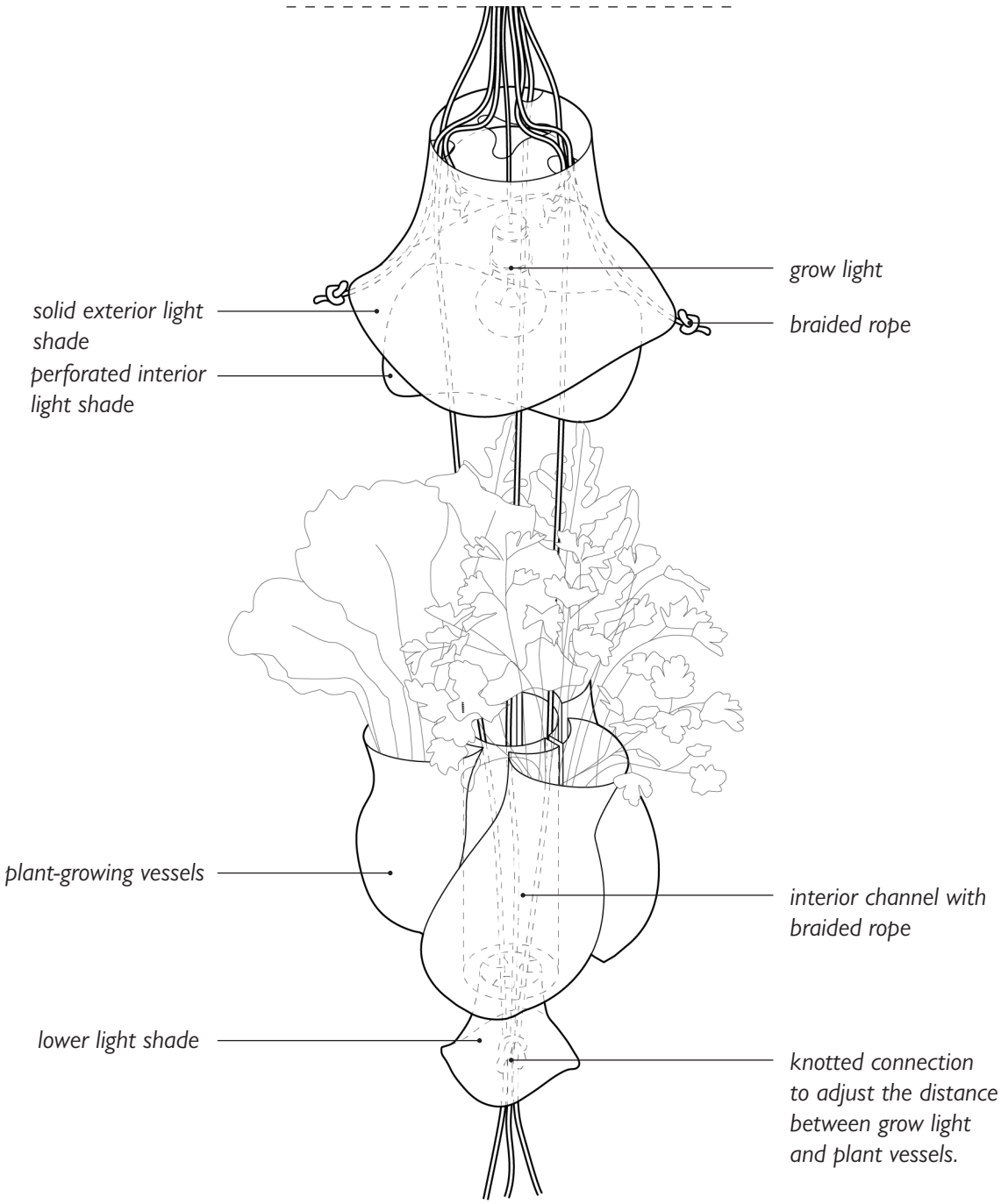


Figure 4.5.1.1 - Revised structural concept for the proposed plant-centric architecture. Diagram by Yannik Sigouin.

4.5.2 – Upper Light Shades

The method for creating light scoops was applied to the exterior light shade at the three high points of the waving edge (Figure 4.5.2.1). This created a vertical channel, allowing the braided rope to be woven into the component. To continue the pattern established by integrating the light scoops at the seams, a woven texture was carried across the surface of the light shade.

The method for creating light scoops was also applied to the interior light shade to create light apertures. Different sizes of scoops, including 2 mm and 4 mm apertures, were iteratively tested to determine which produced the most desirable lighting quality. This shade is designed to be nested in the exterior shade.

The suspension system for the exterior and interior light shades needed to remain separate to test methods for adjusting the position of the exterior shade relative to the interior shade. The interior shade features the same three structural loops at the base as the previous iteration, providing an opening for the braided rope. The exterior light shade has a closed base with three openings aligned to the braided rope channels. At the top of the channel, the rope can be threaded through these openings to the shade's interior. The ropes can then exit the shade through a central opening in the base. This allows all the suspension ropes from the two light shades and the electrical wires to form one central cable reaching the ceiling.

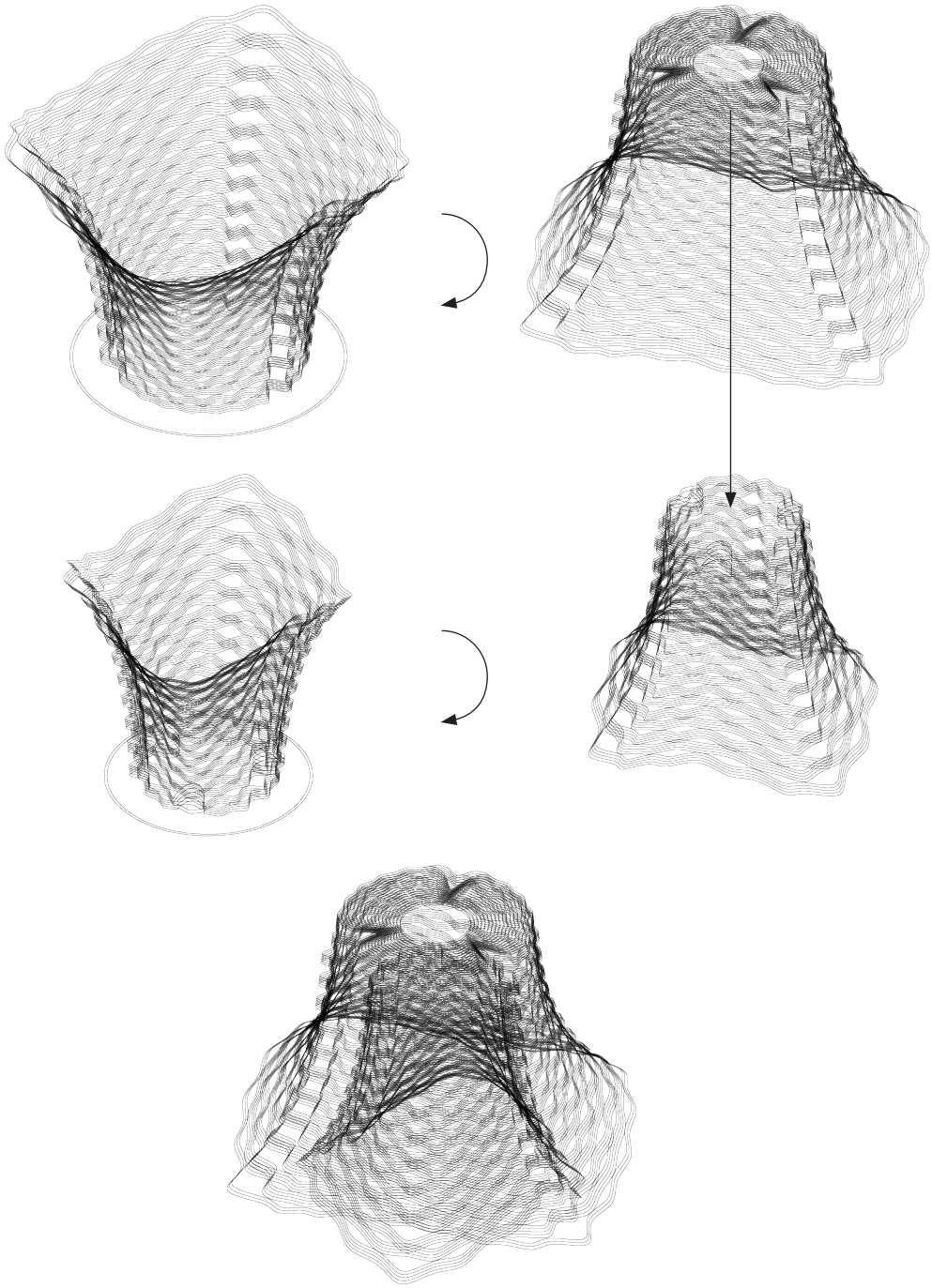


Figure 4.5.2.1 - Print orientation and nesting configuration of light shades.
Diagram by Yannik Sigouin.

Grasshopper Scripting

The light shades were modelled using Grasshopper scripting to obtain a desired piece that would serve the functional needs of the component within the overall system (Figure 4.5.2.2). A base curve was primarily generated to create the top of the light shade. The size 140mm was selected for its proportional aesthetic qualities and its ability to accommodate a light bulb and all structural members to fit through. Guide holes for the light bulb and the rope both accounted for the shrinkage of clay once dried and fired, and Grasshopper was used to generate a tool path to fill in any solid voids needed. The base curve was then translated 200mm upwards to create the height of the light shade, producing the component max height parameter. The top curve was then divided into size points, where each second point would be translated down by 40mm (to clear the Lutum 4.6 3D printing bar) to create the desired undulating look, adding a z-stepping 3D print articulation. The top and bottom curves were then tweened by a maximum distance of 2mm (the desired layer height) to produce contour lines for the tool path to follow. The top undulating curve was then scaled in the xy axis to produce the desired opening for the base of the light shade. Following the scaling of this curve, the tween curves generated followed suit to create a seamless flow of contour lines between the curve extents. The Grasshopper script was then modified to control the curvature of the tween curves to produce a more desirable silhouette of the light shade, keeping in mind reasonable steepness as it was known that the piece might collapse under extreme flares.

To produce the light scoops studied, the curves were grouped into layers of five contours each, occurring in true-false intervals. Each group within one of the two types of intervals followed the same dispatch ruling, where the individual curves were divided into a series of points that offset in inside and outside patterns. Where the curves were at their highest peaks, the three ‘corners’ created by the undulating process, the offset distances of the points extended twice as much to accommodate for the rope to feed through, providing structural support within the printed piece.

A series of two circles were added by offsetting the base curve to create a skirt that would be printed before the piece was. This ensured a consistent flow of the clay before starting the piece. The final move that the Grasshopper script provided was to translate all the curves by 1mm to clear the print bed and then automatically move to the origin of the print bed (50, -50, 0). From here, the piece is ready to print and run through the Grasshopper script to generate a G-code for the Lutum 4.6 clay 3D printer to read.

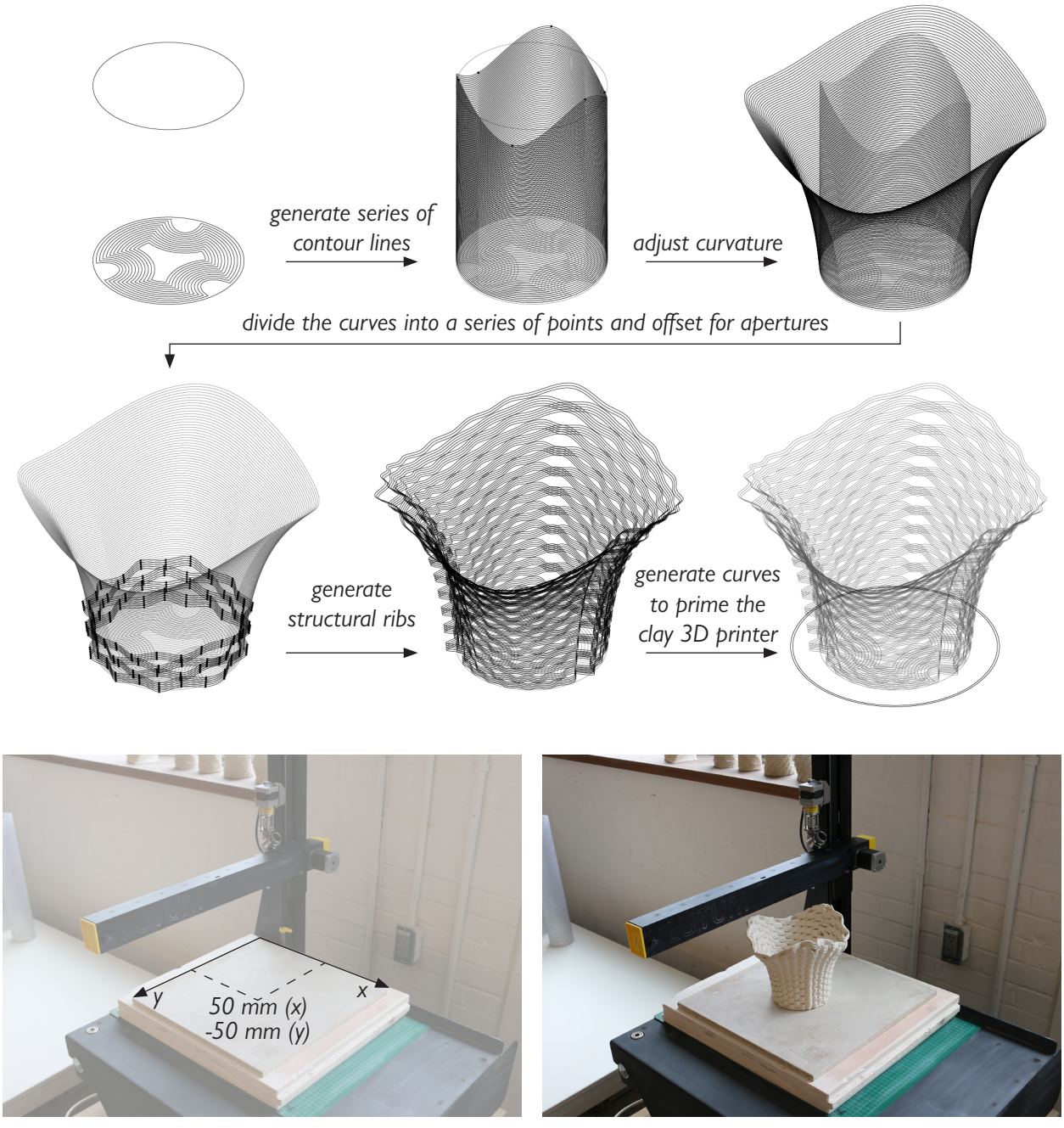


Figure 4.5.2.2 - Summary of light shade design progression using Grasshopper.
Diagram by Yannik Sigouin.

4.5.3 – Test Assembly & Light Studies

The suspension system was woven into the two light shades and nested into one another (Figure 4.5.3.1). The feasibility of adjusting the position of the exterior light shade was tested by pulling the length of rope through the seam to move the light shade up. Friction between the braided rope and the ceramic seam made pulling the rope through the shade difficult. Individually adjusting the lengths of the three braided ropes causes the exterior shade to become off-level, occasionally causing it to hit the interior shade. Lastly, separating the suspension elements of each of the two light shades complicates the structural strategy and results in six separate ropes of different lengths that must be gathered at the top of the light shades. This creates a very thick cable at the top of the system, which is not in reasonable proportion to the other components of the light fixture.

Lighting tests were performed to test the quality of light created by the 2mm and 4mm apertures. The tests demonstrated that the 2mm apertures were not large enough to produce the desired lighting effects (Figure 4.5.3.2). The 4mm apertures produced a subtle and attractive lighting quality across the light shade (Figure 4.5.3.3). The lighting tests also demonstrated that nesting the two shades prevented light from being visible on the exterior shade and did not create the desired lighting quality.

Since nesting the two light shades complicates the structural strategy and prevents the desired light qualities from being produced, it was decided to use only one light shade. The 4mm exterior shade was the preferred option. However, the size of the exterior light shade and the thickness of the braided rope were slightly too large in proportion to the rest of the light fixture. Moving forward, the size of the exterior light shade was reduced by 10%, and the ¼” rope was substituted for ⅛” rope.



Figure 4.5.3.1 - Assembly of nested light shades.
Photo by Yannik Sigouin

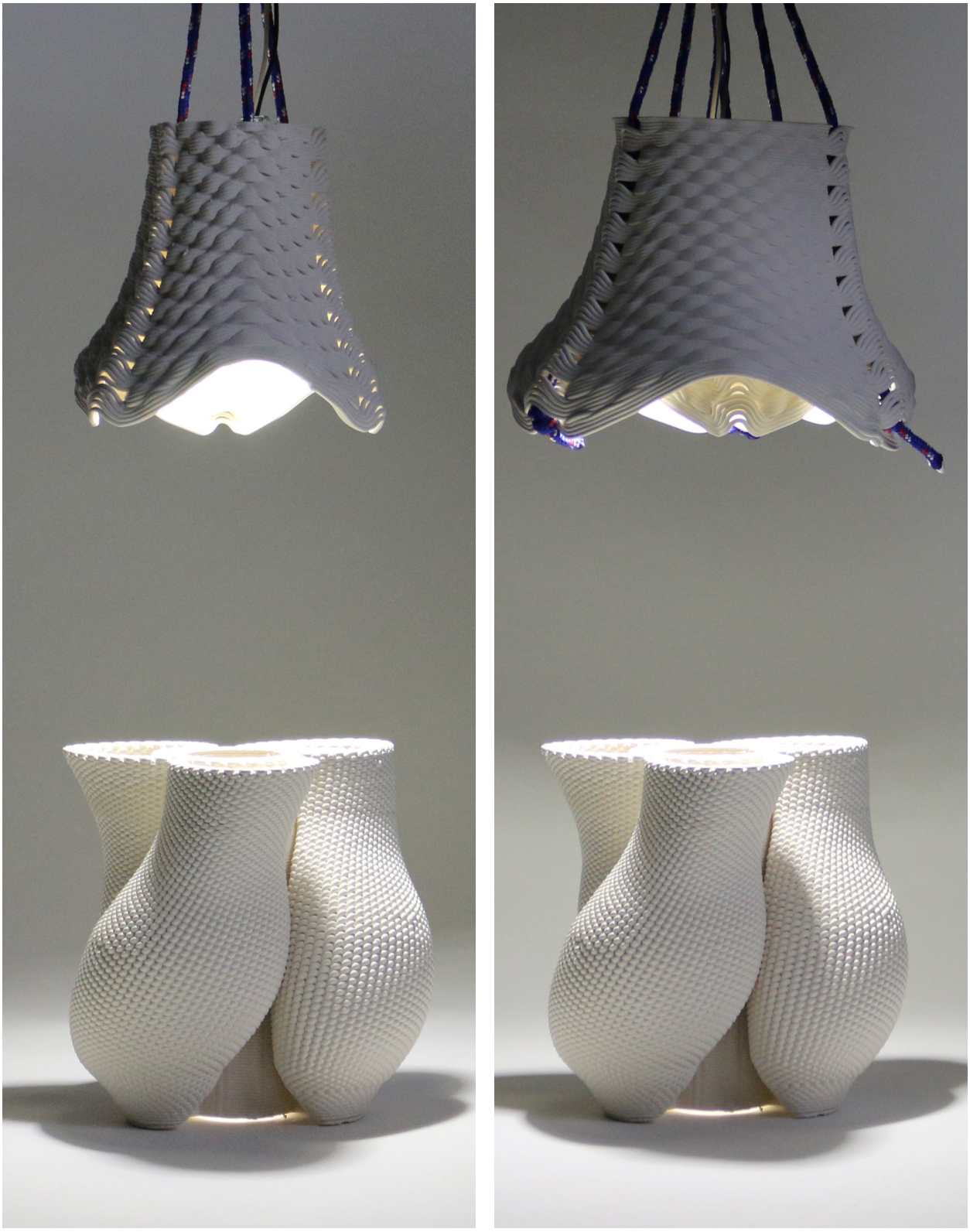


Figure 4.5.3.2 - 2mm aperture interior shade (left), 2mm aperture shades nested (right).
Photos by Yannik Sigouin



Figure 4.5.3.2 - 4mm aperture interior shade (left), 4mm aperture shades nested (right).
Photos by Yannik Sigouin.

4.5.4 – Plant Growing Vessels & Lower Shades

The massing and methods of creating structural connections for the plant-growing vessels and lower light shade largely remained the same. The separation between print layers at the base of the plant growing vessels was observed in prints that used a smooth tool path—dispatching points on the tool path to create texture prevented print layers from separating through drying (Figure 4.5.4.1). New patterns were experimented with to minimise print layer separation and visually connect the appearance of the plant-growing components with the textures created in the upper light shades (Figure 4.5.4.2 - 4.5.4.3). These patterns incorporated fluted and woven effects and were applied to the lower shade. A vertical seam was added through the centre of each plant-growing vessel to continue the linear movement created by the dispatched seam in the upper light shades.

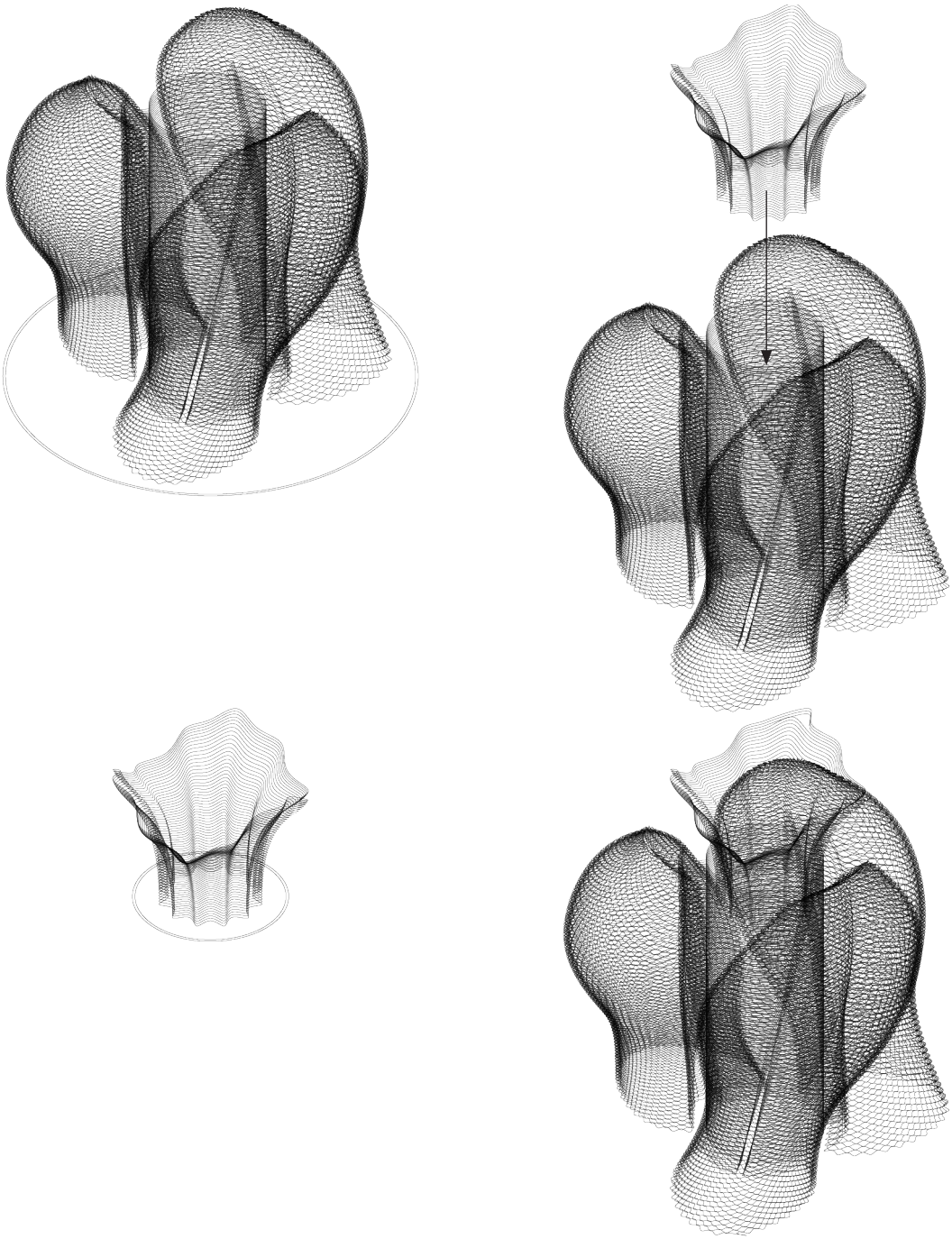


Figure 4.5.4.1 - Print orientation and nesting configuration of plant-growing vessels and lower shade. Diagram by Yannik Sigouin.



Figure 4.5.4.2 - Different textures and patterns were created for the plant-growing component. Photo by Yannik Sigouin.



Figure 4.5.4.3 - Fluted textured lower shade nested in the interior channel of a woven + ribbed textured plant-growing vessel. Photo by Taylor Murray.

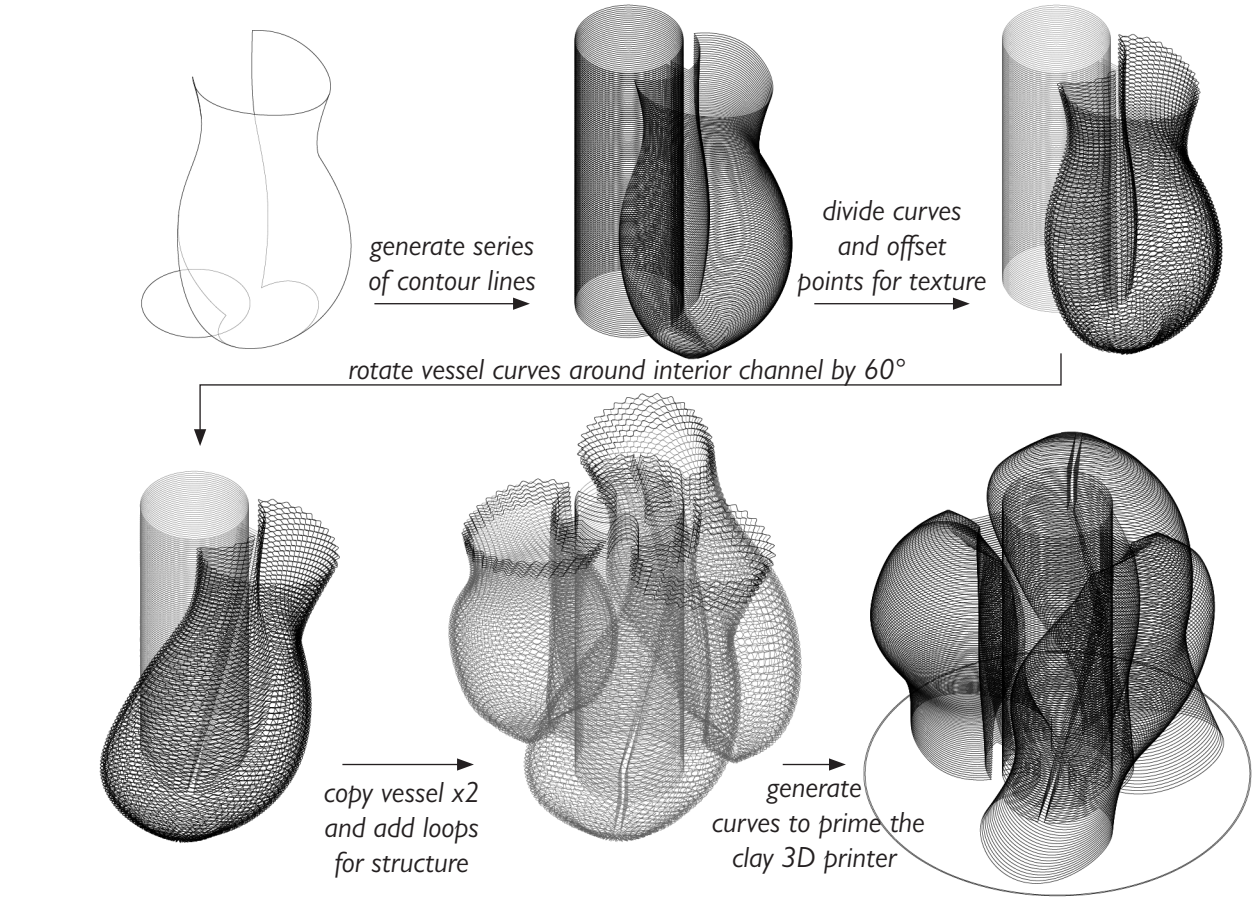
Grasshopper Scripting

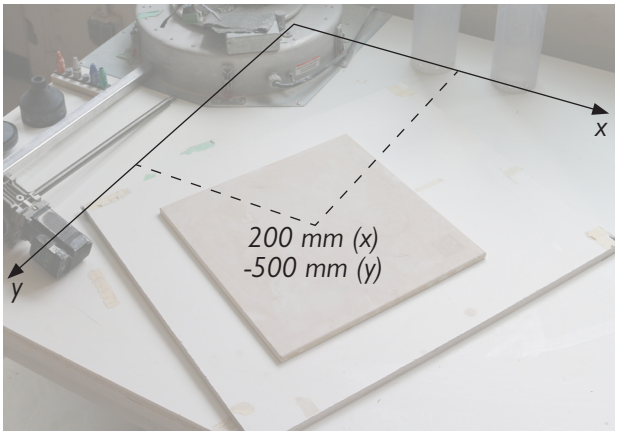
In the phase 1 prototype, the plant-growing vessel was 3D-modelled in Rhinoceros 3D. Grasshopper was implemented in this phase 2 prototype process for more aesthetically pleasing and optimal control of shaping the component (Figure 4.5.4.4). Rhinoceros 3D generated one vessel to produce a guide massing to start the design. A circle with a radius of 45 mm was generated to create a base for the interior channel for the structural assembly to pass through. The modelled vessel unit was then translated to the circle, offset from the base circle's centroid by 60mm. The vessel was then contoured by 2mm intervals using Grasshopper to generate a series of base curves to manipulate parametrically. The base circle was then translated vertically by 2mm intervals to match the layer height of each generated contour of the modelled vessel. A series of lines connected each layer of the vessel contours to the corresponding circle's contours to produce a connective structure between the interior compartment and the vessel.

The contours of the vessel were then dispatched so every second layer followed the same rule; the curves were divided into a series of points, which were alternatively offset to create a weaving pattern. This weaving pattern not only added an aesthetic element to the piece but also helped with the overall adherence of each layer, as each contour line has more surface area to adhere to the preceding layer below. The series of contour lines of the vessel were then rotated around the centroid of the base circle so that the difference between the bottom curve and the top resulted in a 60° rotation, while all curves in between rotated accordingly. This step generated the individual flow of one vessel, which then was generated to rotate two more times to produce the three individual vessels of this component. The top 5 curves were selected, and three loops were added, each within the circular channel, to create structural members for the suspension system to feed through.

The overall series of generated curves was flipped upside down, as the print needed to be printed upside down to produce the desired smooth tops and curved bottoms. Like the final process of the light shade, a series of circular curves were generated to create a skirt. The curves were then translated vertically by 1mm and relocated to the centre of the Scara printer's printing bed (200, -500, 0).

The process for the lower shade follows that of the top light shade, but with less detail focused on the texture. It was a simple print, following the same steps as the light shade. The focus was to generate the piece's base to be smaller than the radius of the vessel's interior channel, accounting for the shrinking caused by drying and firing. Like the vessel, three loops were added to the five base curves of the shade to produce structural support for the suspension system to fasten to.





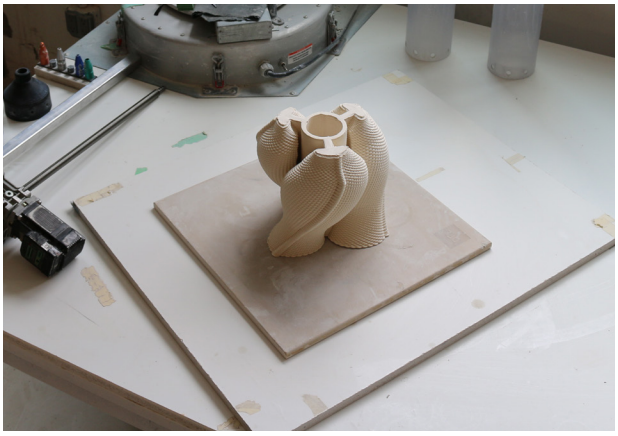


Figure 4.5.4.4 - Summary of plant-growing vessel design progression using Grasshopper. Diagram by Yannik Sigouin.

4.5.5 – Assembly

The system's assembly is divided into the upper light shade, the plant-growing vessels, and the lower shade (Figure 4.5.5.1). To assemble the upper light shade, ⅛" braided rope is threaded through the vertical seam. The rope is woven around the layers at the top of the light shade and knotted to hold it in place. The knot is then tucked back into the structural seam to conceal the extra length of the rope. The opposite end of the rope is woven into the base of the light shade. These steps are repeated for each of the three structural seams.

The grow light connects to the system at the base of the light shade. The central opening in the base is large enough for the metal clip of the light socket to be pulled through. This causes the top face of the light socket to be flush against the base's interior, allowing the grow light to be levelled (Figure 4.5.5.2).

To assemble the second half of the system, three lengths of rope are threaded through the structural loops in the lower shade, then through the loops in the plant-growing vessels, and lastly, through three openings at the perimeter of the base in the upper light shade (Figure 4.5.5.3).

The distance between the top of the plant-growing vessels and the light bulb is then adjusted to 12" - 16" (Figure 4.5.5.4). The three lengths of rope are tied into a knot beneath the lower shade to hold the plant-growing vessels in this position. The system can then be suspended, and plants may be placed in each vessel (Figure 4.5.5.5).

To remove the plant-growing vessels from the system or alter the distance between the plants and the grow light, the vessels and lower shade are held up, and the knot is undone (Figure 4.5.5.6). The plant-growing vessels can then be detached from the system for cleaning and maintenance (Figure 4.5.5.7). Alternatively, the knot can be repositioned lower in the system to create a greater distance between the plants and the grow light.



Figure 4.5.5.1 - Assembly components of the plant-centric architecture prototype phase 2.
Photos by Yannik Sigouin



Figure 4.5.5.2 - The braided rope is threaded through the vertical seam and knotted (top left). The opposite end of the braided rope is woven into the base of the light shade (top right). The grow light connects to the system at the base of the light shade (bottom left). The metal clip of the bulb, along with the electrical wires, are pulled through the opening in the base (bottom right).

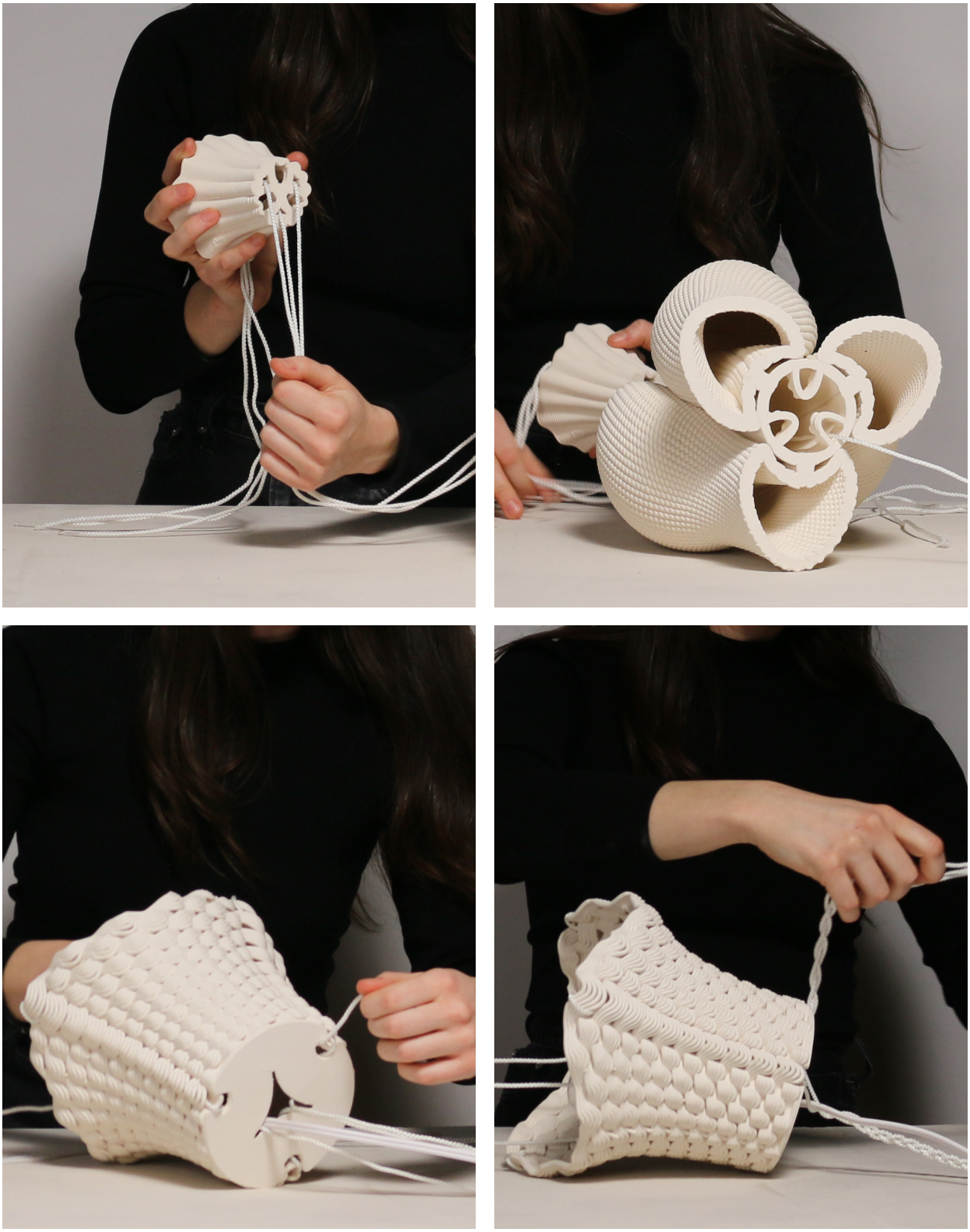


Figure 4.5.5.3 - Three lengths of braided rope are threaded through the lower shade (top left) and the plant-growing vessles (top right). The same lengths of rope are then threaded through the upper light shade (bottom left) and then braided together (bottom right). Photos by Yannik Sigouin.



Figure 4.5.5.4 - The system can then be suspended (left). The grow light can be turned on and set to an automated light cycle (right). Photos by Yannik Sigouin.



Figure 4.5.5.5 - Plants can be placed in each of the three growing vessels (left). The system can now be adjusted (right). Photos by Yannik Sigouin



Figure 4.5.5.6 - To adjust the position of the system, the components are held up, and the knot underneath the lower shade is undone (left). The knot can be repositioned to alter the distance between the plant vessels and grow light (right).
Photos by Yannik Sigouin



Figure 4.5.5.7 - Complete plant-centric architecture prototype phase 2 assembly.
Photo by Yannik Sigouin.

4.5.6 – Glaze

Glaze was applied to the ceramic components to add colour, enhance the surface texture quality, and make the plant vessels impervious to water. Several cone 6 glazes were used to test tiles in various colours and were often layered together to produce new shades (Figure 4.5.6.1). These glaze tests determined that the most effective combinations included a neutral or white base with hints of colour. Large amounts of colour were overpowering when applied to the entire tile; however, hints of colour provided an element of customisation, created visual interest, and complimented the colours in the plant life.

The finish and thickness of the glaze applied to the ceramic components were also important considerations. Matte-finish glazes prevented light reflection and scattering and often concealed the appearance of the tool path. Glossy finishes were preferred as they enhanced lighting effects and highlighted surface qualities. The thickness of the glaze applied also determined the surface character. If the glaze were too thick, it would hide the texture created by the tool path and add thickness to the components, preventing them from nesting together. Glazes with appropriate water highlighted the tool path, allowed pieces to connect, and coated the components thoroughly enough to make them impervious to water. Glazes were purchased in powdered form and mixed with a custom ratio of distilled water to achieve the desired glaze thickness. The preferred ratio discovered through these tests was 10 lbs of dry glaze to 6 L of distilled water.

The final cone 6 glazes chosen were ‘White Opal’ as the base shade and ‘Dark Flux’ as the contrast shade. Dark flux is a glaze enhancer formulated to be layered over other glazes, as it reacts with each glaze to pull out new colours and create movement. When applied over White Opal, it produces bright blue to black colours. It was used to specific parts of the component to highlight their features, such as the vertical channel of the upper light shade, the seam of the plant growing element, and the waving edge of the lower light shade.

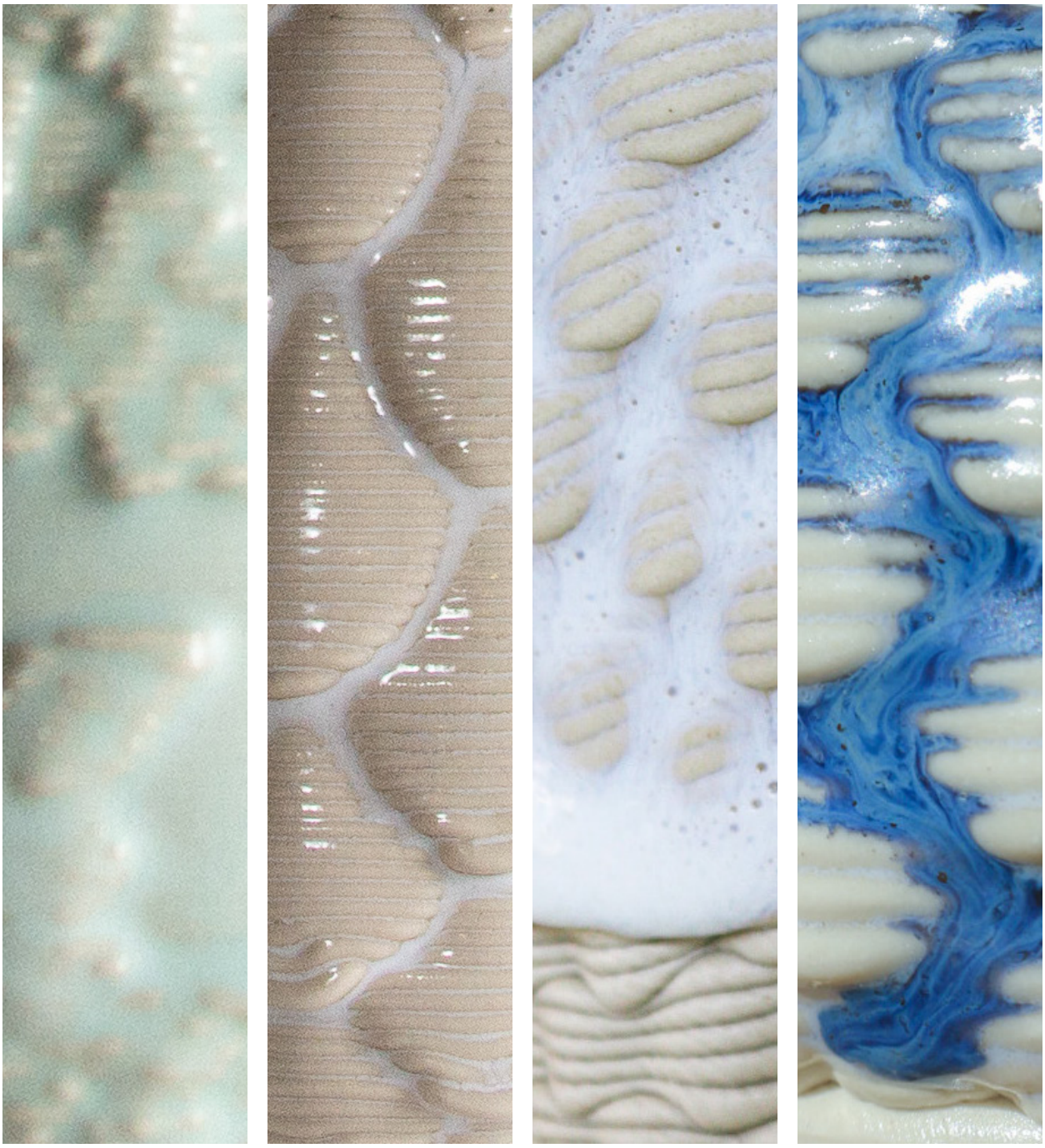


Figure 4.5.6.1 - Matte glazes in shade wintergreen (left). Glossy glazes in white opal (middle left). Glaze application that was too thick (middle right). White opal and dark flux are layered together (right).
Photos by Taylor Murray.

These glazes were applied to each fixture's three ceramic components and fired in the kiln at cone 6. Unfortunately, the mid-range glaze cone 6 firing of the actual 1:1 cone 06 bisque components revealed several issues that were not present during the glaze tests. The glaze tests were done with the same Pottery Supply House #516 clay body and firing temperatures but were done with smaller scales ranging from 0.5:1 to 0.75:1. The thickness of the prints stayed the same between both clay 3D printing scales, meaning the 1:1 clay 3D printing thickness is proportionally thinner. First, the glaze colours became muddy and patchy when applied to the components of the system. It is unclear what caused this, but variations in kiln firing temperatures are a possible explanation. Second, the glaze applied to the interior of the plant vessels dripped out the component and caused it to fuse to the glaze tray. This occurred due to the method for applying glaze to the inside of the element. To apply glaze to the plant vessels, the wax resist was first brushed onto the top 1 cm of the lip of the vessels to provide an area where the glaze could not adhere and prevent the component from fusing to the glaze tray during firing. The inside of the plant vessels was then filled with glaze and tipped upside down to allow the extra glaze to drain out of the vessels. However, this method likely created a glaze application on the inside of the vessels that was too thick, causing the glaze to flow past the wax resist area during firing and completely fuse the component to the glaze tray. Lastly and most detrimentally, the light shades experienced excessive warping and collapse during firing due to the clay 3D print thickness proportion and curve shape of the shade (Figure 4.5.6.2).



Figure 4.5.6.2 - The glazes on the component became patchy after firing and produced a different result from the glaze test (top left). Excess glaze in the plant vessles caused the component to fuse to the glaze tray (bottom left). The glaze firing caused the upper light shades to warp and collapse (right). Photos by Taylor Murray.

To move forward and address the issues caused by the cone 6 glaze firing, a second glaze test opted to try firing at cone 06 with a low-fire glaze. Furthermore, it was tested to fire the vessel components with the openings facing upwards to allow the glaze to pool inside the vessels. This orientation of glaze firing minimised the surface area for the glaze to fuse to the drip plate and allow the top lip of the vessels to stay bare. The final successful iteration of the glaze pieces was done following the same process as the cone 6 trial, but the finished product was done with the cone 06 glaze '2709 Cappuccino Mint Jungle Gem' by Mayco (Figure 4.5.6.3 - 4.5.6.5).



Figure 4.5.6.3 - Glaze was applied to the cone 06 bisque fired pieces (top). Successful glaze fire at cone 06 with Mayco's '2709 Cappuccino Mint Jungle Gem' (bottom).
Photos by Yannik Sigouin



Figure 4.5.6.4 - Successful glaze fire detail shots of the three components.
Photos by Yannik Sigouin



Figure 4.5.6.5 - Glazed plant-centric architecture prototype phase 2 assembly inhabited by plants.
Photo by Yannik Sigouin

CHAPTER 5 – CONCLUSION

5.1 – PROTOTYPE FINDINGS

5.1.1 – Phase 1

The first phase successfully created all the required components for the system with appropriate massing and proportional relationships. However, as part of the iterative design intention, each component required further revisions to meet the design requirements determined by the schematic design phase.

Firstly, as the components were not fully developed, the plant-growing vessels could contain only 0.4 L of water, less than the specified 0.5L – 1.0L. Light tests could be conducted for this prototype by removing the structural cables that connected the plant-growing vessels to the interior light shade (Figure 5.1.1.1). These tests revealed that due to the brightness of the grow lights, the upper light shades need to cover more of the light bulb to prevent harsh, direct light from reaching the residential space. Further iterations of these components will focus on designing ways to control the quality and intensity of the light emitted from the fixture. In addition, the upper light shades will require a central opening to allow the grow light to be correctly installed and levelled in the system. Lastly, the support and suspension elements must be revised so as not to interfere with the grow light that runs through the centre of the system. Consideration will be given to designing connections between adaptable structural elements and allowing system components to be adjusted or removed as required.



Figure 5.1.1.1 - Light study using completed plant-centric architecture prototype 1 components. Suspension structure removed to incorporate light fixture for light testing.
Photo by Yannik Sigouin.

5.1.2 – Phase 2

Based on the successes and challenges of the first prototype phasing, the following further enquiries were prioritised for prototype phase 2:

- Print all components on a 1:1 scale.
- Revise the design of the upper light shades to control the intensity of the light emitted from the grow light.
- Reconsider the materials and design of the structural system to allow for the proper installation of the grow light.
- Design adaptable structural connections and allow components to be adjusted or removed from the system.

Attention was given to developing the system's aesthetic details and textural qualities (Figure 5.1.2.1). While the above goals were accomplished, many design elements could be explored further in future iterations. For instance, the components from the previous iteration were increased by 25% to be fabricated at a 1:1 scale and to achieve an interior volume of 0.5 L for the plant-growing vessels. This was the largest size that the plant-growing component could be scaled to, as it used all the clay that could be contained in the 3600cc extruder tube. Further iterations of this system could consider modifying the design of this component to allow the plant vessels to include more than 0.5 L of water and enable plants of larger varieties to be grown in the system.

The design of the light shade was refined to prevent bright, direct light that causes viewing discomfort. Increasing the size of this component by 25% allowed the shade to conceal the profile of the grow light, reducing the amount of light emitting into the indoor space. To further control the quality and character of light across this component, small openings were created on the surface of the shade to produce light apertures (Figure 5.1.2.2 - 5.1.2.4).

Additional openings were created in the light shade to produce vertical channels into which the braided rope could be woven. This directed the structure away from the plant-centric system's centre, where clear space for installing the grow light was required. A central opening in the base of the light shade allows the grow light to be levelled in the system, allowing the grow light to be installed correctly in this iteration.

The design of the plant-growing vessels and lower shade were developed to create a tactile and engaging quality. Surface textures were experimented with with the algorithmic modelling software Grasshopper by offsetting toolpath points to create stippled, fluted, and woven effects. The position of the grow light above enhances the appearance of the surface texture. Light is washed across the stippled surface of the plant-growing vessels, and the fluted pattern is on the lower shade. In addition, the light that shines through the interior channel of the plant-growing vessel casts a single projection onto the floor below that resembles a flower (Figure 5.1.2.5). This outcome was not anticipated in the design process but is enjoyed as a system feature.

Lastly, the structural design was revised to create flexible connections with added 3D printed plant baskets (Figure 5.1.2.6 - 5.1.2.7). The plant-growing vessels can be repositioned or removed from the system by moving or untying the knot underneath the lower shade. However, this process requires two people–one to hold the plant vessels and lower shade, while the other person unties and repositions the knot.

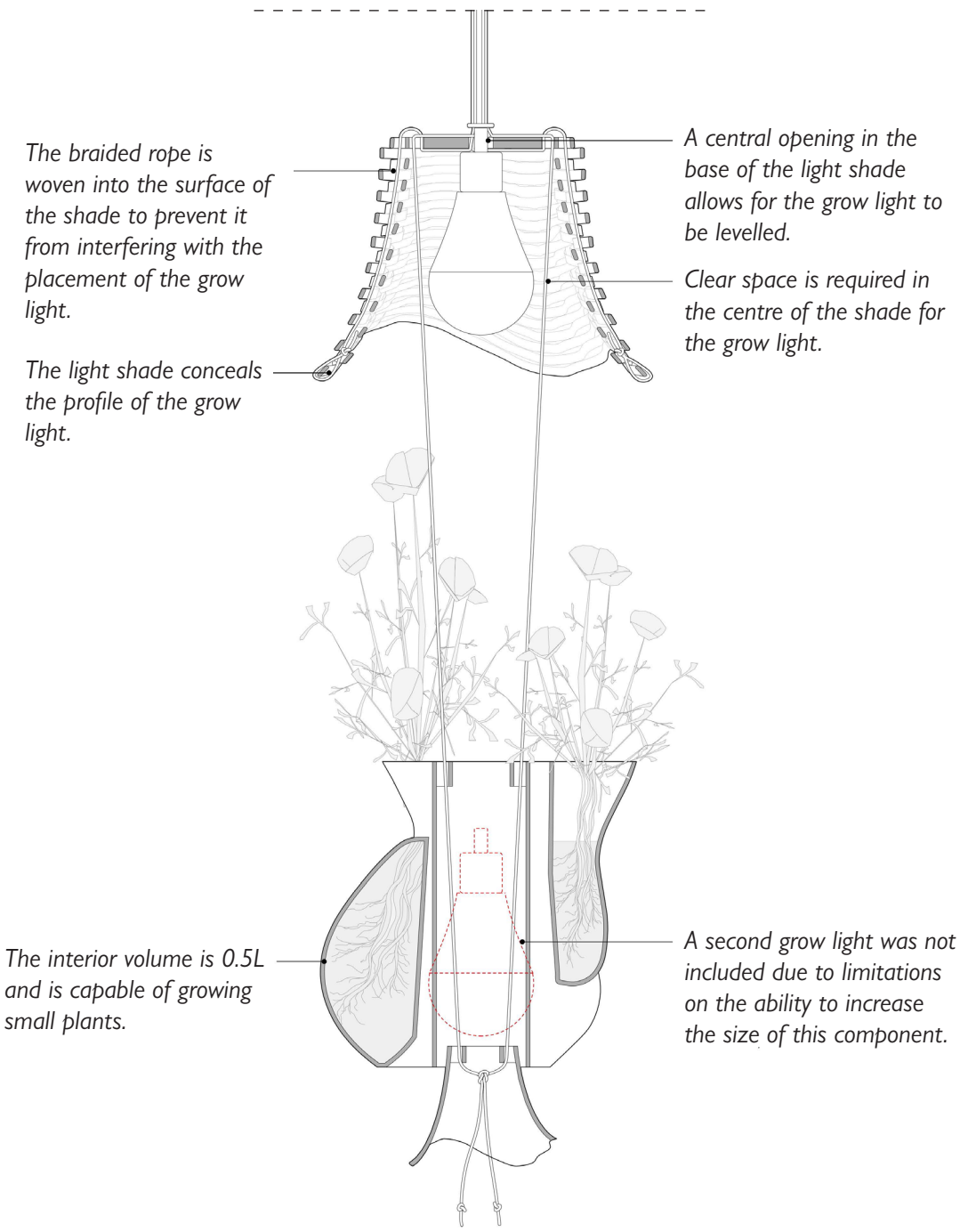


Figure 5.1.2.1 - Diagram showing the revised plant-centric architecture prototype system for assembly. Diagram by Taylor Murray.

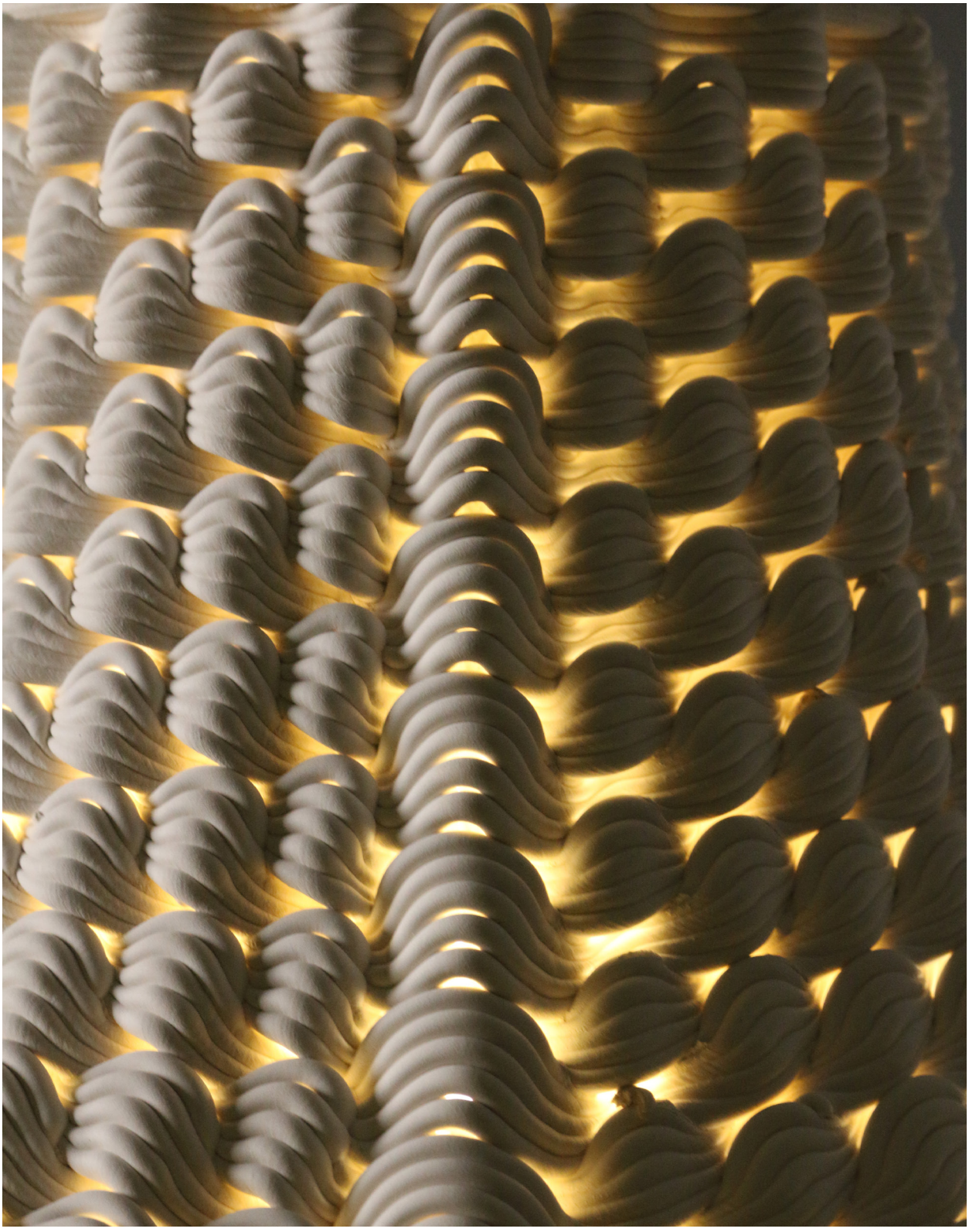


Figure 5.1.2.2 - Detail photo of the bisque-fired upper light shade apertures.
Photo by Yannik Sigouin.



Figure 5.1.2.3 - Detail photo of the glaze-fired upper light shade apertures.
Photo by Yannik Sigouin.

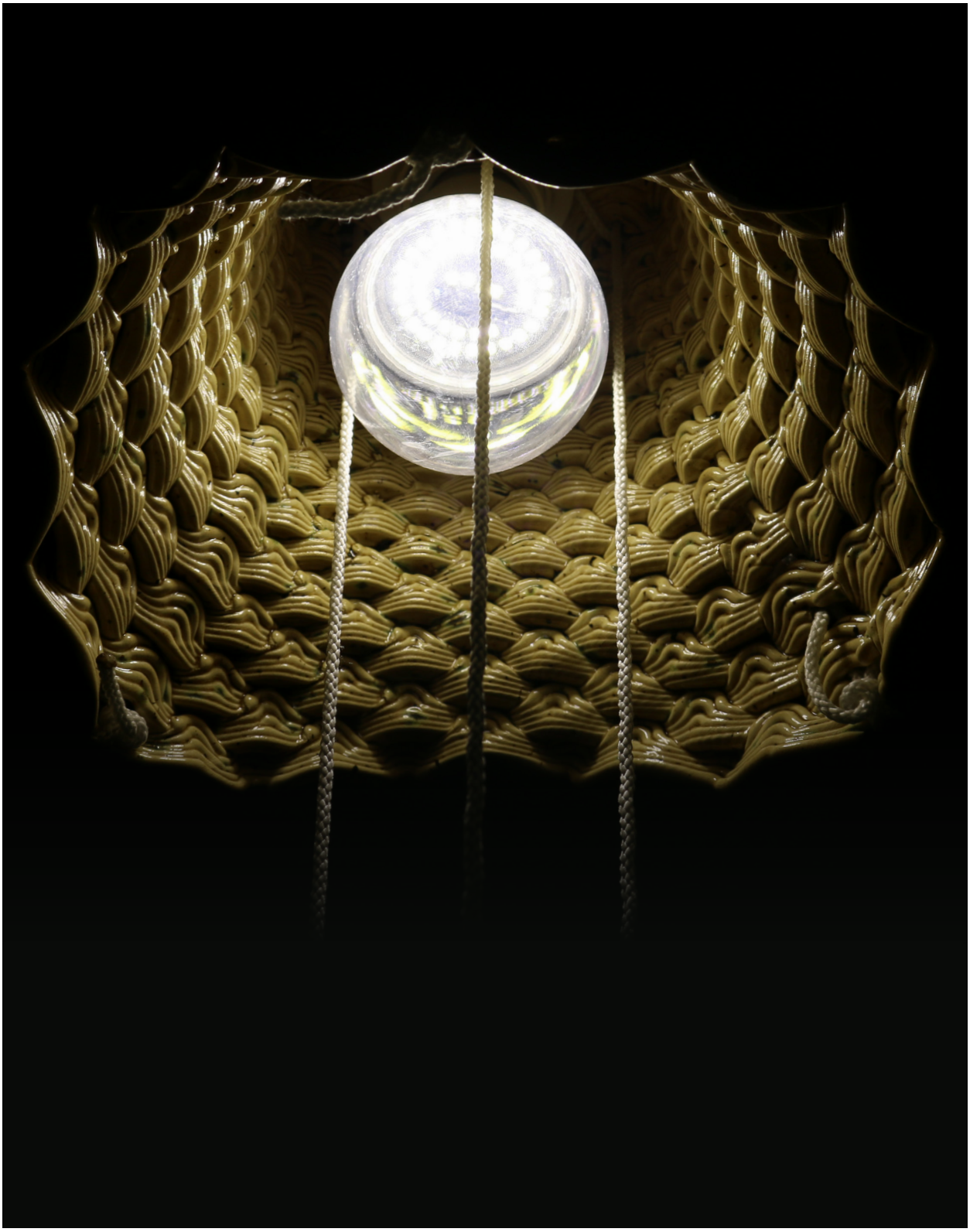


Figure 5.1.2.4 - Interior shot of the glazed upper light shade.
Photo by Yannik Sigouin.

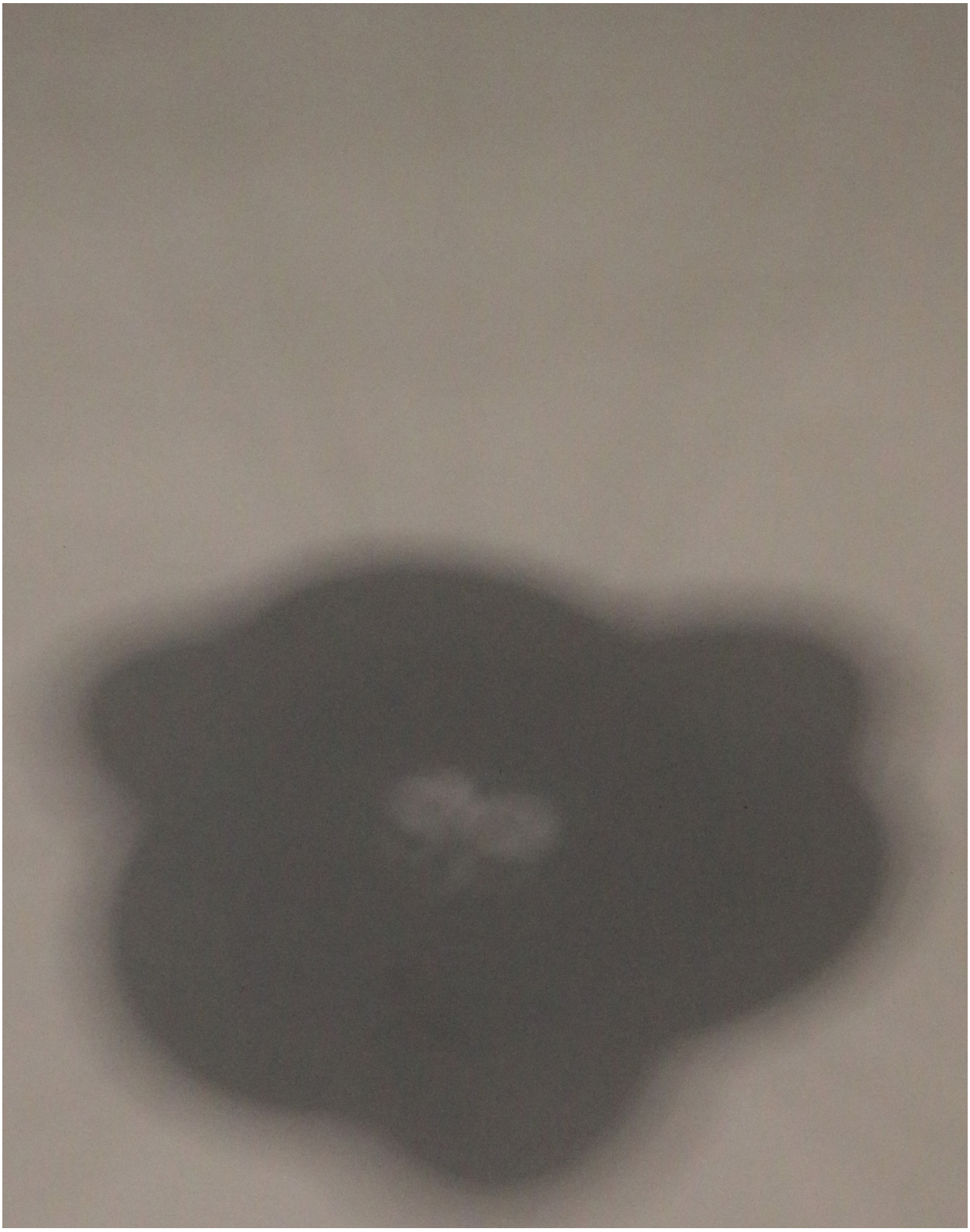


Figure 5.1.2.5 - A projection of light is created below the system that resembles a flower.
Photo by Yannik Sigouin.



Figure 5.1.2.6 - Custom 3D-printed baskets were made to house each of the plants to fit within the vessels. This ensured the plants could be suspended above the water within the vessels and eased the ability to add and remove plants from the system.
Photo by Yannik Sigouin.



Figure 5.1.2.7 - Plants inhabiting the plant-centric architecture prototype vessels.
Photo by Yannik Sigouin.

5.2 – FUTURE DISCUSSION

This thesis represents a snapshot in the iterative process of clay 3D printing, specifically within the context of designing clay 3D printed components that cater to plant growth. While significant research contributions have been made in this thesis, the iterative research process remains ongoing, with many potential iterations and explorations yet to be undertaken. The following are speculative directions and questions for future iterations and explorations, intended to push the boundaries of this work and build on the foundation of knowledge developed in this thesis to deepen its impact on plant-centric architecture:

Glaze Development

- Explore glazes that enhance apertures, allowing light to penetrate the vessel walls while maintaining structural integrity.
- Investigate glazes that improve the water-tightness of the vessel components, ensuring longevity and functionality in diverse environments.
- Develop glazes that alter the thermal properties of the vessels, potentially creating microclimates suited to specific plant needs.

Vessel Sizes

- Create a series of vessels where each is tailored to the specific needs of different plant types, such as varying root depths, moisture requirements, or growth patterns.
- Design vessels with modular components that allow for easy resizing or reconfiguring to accommodate plant growth stages or changes in plant species.

Light Integration

- Revisit the concept of placing the light source at the bottom of the vessel, ensuring optimal light distribution for plant growth.
- Investigate the use of bioluminescent materials as a potential alternative light source within the vessels.

System Design

- Design a more flexible system that allows for easier adjustments and customisation, reducing the physical strain and technical expertise required for use.
- Focus on optimising the overall system design to make it more sustainable, reducing energy and material consumption during the manufacturing and operational phases.

Printing Techniques

- Refine printing techniques to create vessels that support root aeration and drainage, directly contributing to healthier plant growth.
- Develop surface textures and patterns that improve water retention or distribution, catering to specific plant types.
- Explore the potential for creating multi-layered structures within the vessels, allowing for varied moisture gradients.

Material Exploration

- Investigate alternative clay compositions, including the incorporation of organic materials, to enhance the compatibility between the vessel and the plant's needs.
- Develop hybrid materials that combine clay with other biodegradable substances, potentially creating a vessel that decomposes as the plant grows.
- Experiment with materials that change properties over time (e.g., colour, porosity) to respond to environmental conditions or plant growth stages.

Broader Plant Typologies

- Expand the range of plant typologies beyond food-producing plants to include ornamental species, medicinal herbs, or even aquatic plants.
- Consider the needs of rare or endangered plant species when designing vessels that support conservation efforts.

Human-Plant Interactions

- Explore how the design of these vessels can enhance the human experience, focussing on aesthetics, ease of use, and emotional connection to the plants.
- Investigate the potential for creating vessels that facilitate plant communication or interaction, perhaps through visual or sensory feedback systems.

5.3 – CONCLUSION

This thesis explored ways in which architecture design principles can be applied to methods of designing for plants to create ceramic 3D-printed plant-centric architecture. The fabricated systems are intended to exhibit posthuman design for plants that is aesthetically pleasing, scalable, and responsive.

The plant-centric architecture prototype proposes a hybridised clay 3D printed system to demonstrate how indoor plant-growing systems can be designed to live symbiotically within human-centric architecture. This prototype was developed through an iterative clay 3D printing process that involved the fabrication of several models. Two clay 3D printers were used in this research, the Scara V4 and the Lutum V4.6. The technical capabilities of these clay 3D printers were explored in depth, while progressing the massing and intricate details for the plant-growing systems. Following the creation of each of the prototypes, they were evaluated for their ability to function as practical systems for plant growth.

The plant-centric architecture prototype is a scalable and hybridised system that developed the research objectives and research parameters for designing for plants. The schematic design phase identified several constraints, including parameters for the size of the plant growing vessels, the position of the grow light, and the distance required between the plants and the light source. Beyond these functional considerations, aesthetic details were developed using the capabilities of algorithmic modelling with clay 3D printing to produce a full range of tool path manipulations in the x, y, and z axes. These manipulations result in the dynamic and texture qualities of the prototype, creating intricate surface details, custom system connections, and light apertures. From a functional perspective, the proposed plant-centric architecture is limited in scale and is capable of growing plant typologies of leafy greens and herbs. However, it can demonstrate that architectural design principles can go beyond designing for humans. This, in addition to its beauty, scale, and suspended hydroponic system, allows for posthuman awareness to be expressed to those inhabiting the shared space (Figure 5.2.1 - 5.2.4).



Figure 5.3.1 - Plants immediately after they were placed in the system (left). Plants after two weeks (right). Photos by author Yannik Sigouin and Taylor Murray.



Figure 5.3.2 - Uninhabited plant-centric architecture prototype (left). Inhabited plant-centric architecture prototype (right). Photos by Yannik Sigouin.



Figure 5.3.3 - The final result of the plant-centric architecture prototype exploration.
Photos by Yannik Sigouin



Figure 5.3.4 - The final result of the plant-centric architecture prototype exploration.
Photos by Yannik Sigouin.

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Send me a link when you're finished, sounds really interesting, would love to read it. And good luck with it!

Best,

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Good Luck!

Best,

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Congrats on being almost at the finish line :)

Yes, no problem. You have permission to include the images in your document with credits to both myself and James.

Best wishes for the defense,

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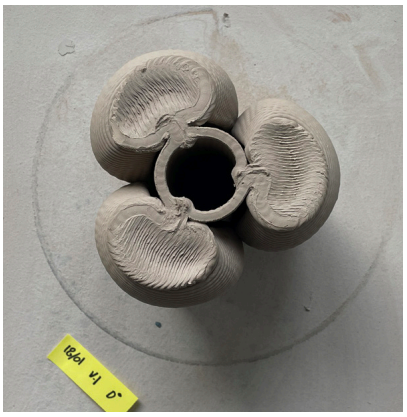
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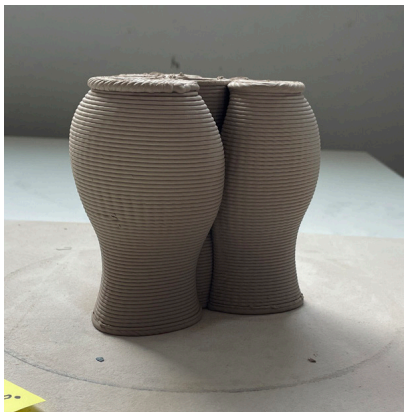
APPENDIX A - PLANT-GROWING COMPONENT PROTOTYPES



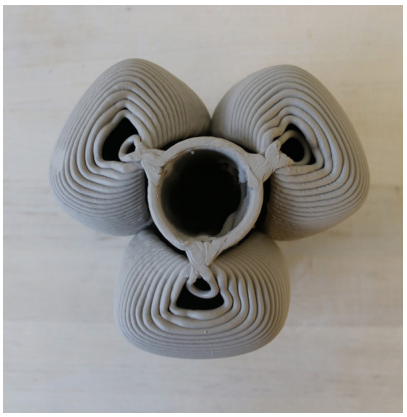
Printing vessels with flat base test 1.



Printing vessels with flat base test 2 (plan).



Printing vessels with flat base test 2 (elevation).



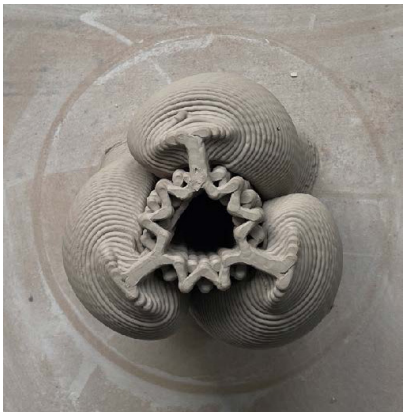
Printing vessels with curved base test 3 (plan).



Printing vessels with curved base test 3 (elevation).



Printing vessels with curved base test 3 (elevation).



Printing vessels with curved base test 4 (plan).



Printing vessels with curved base test 4 (plan).



Printing vessels with curved base test 4 (elevation).



Printing vessels with curved base test 5 (plan).



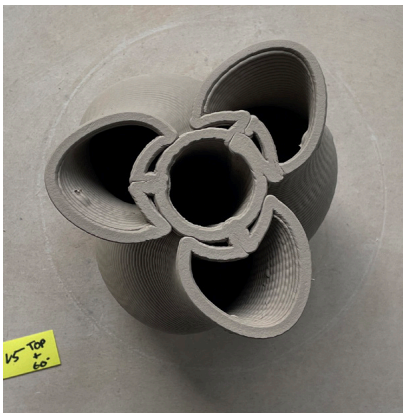
Printing vessels with curved base test 5 (elevation).



Printing vessels with curved base test 5 (elevation).



Printing vessels with curved base test 6 (plan).



Printing vessels with curved base test 6 (plan).



Printing vessels with curved base test 6 (elevation).



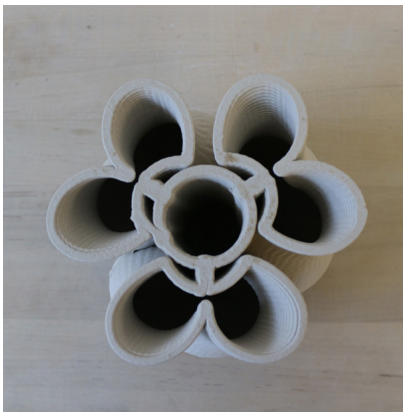
Printing vessels with curved base at 1:1 (plan).



Printing vessels with curved base at 1:1 (plan).



Printing vessels with curved base at 1:1 (elevation).



Six vessels around circular channel test.



Final form (test 6) with structural loops (plan).



Final form (test 6) with structural loops (elevation).



Stippled texture test 1 (plan).



Stippled texture test 1 (elevation).



Stippled texture test 2 (plan).



Stippled texture test 2 (elevation).



Fluted texture test 3 (plan).



Stippled texture test 3 (elevation).

APPENDIX B - LIGHT SHADE COMPONENT PROTOTYPES



Angle test for cone shape.



Isocurve test 1 (plan).



Isocurve test 1 (elevation).



Isocurve test 2 (plan).



Isocurve test 2 (elevation).



Isocurve test 2 (perspective).



Isocurve test 3 (plan).



Isocurve test 2 (elevation).



Isocurve test 4 (plan).



Isocurve test 4 (elevation).



Isocurve test 5 (exterior shade, plan).



Isocurve test 5 (exterior shade, elevation).



Isocurve test 6 (interior shade, plan).



Isocurve test 6 (interior shade, elevation).



Nesting shades test.



Isocurve test 7 at 1:1 experiencing distortion.



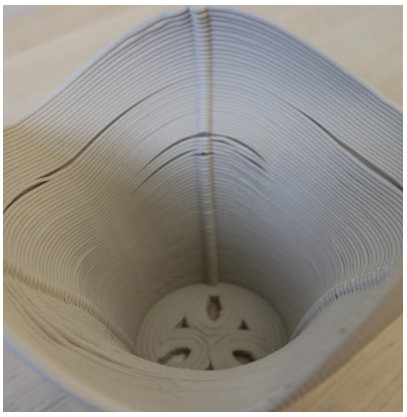
Isocurve test 7 at 1:1 experiencing collapse.



Isocurve test 8 at 1:1 experiencing collapse.



Isocurve test 8 with three ribs experiencing cracking (plan).



Isocurve test 8 with three ribs experiencing cracking (perspective).



Isocurve test 9 with six ribs remains intact (plan).



Woven texture test 1 (plan).



Woven texture test 1 (elevation).



Woven texture test 2 (elevation).



Woven texture test 3 seperating at seam condition (elevation).



Woven texture test 4 experiencing collapse (plan).



Cracking at structural base of the light shade (plan).

APPENDIX C - GLAZE TESTS



White Opal.



Wingergreen.



SW 194.



SW 197.



SW 196.



Oyster.



SW 198 over SW 195.



SW 190 over SW 195.



Cobaltic Sea.



SW 195.



SW 193.



SW 191 over SW 193.



SW 511.



SW 192.



SW 198.



SW 190.



SW 191.



SW 512 over SW 193.

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