RIPPLE
An Investigation Into 3D Printing Ceramics

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Introduction

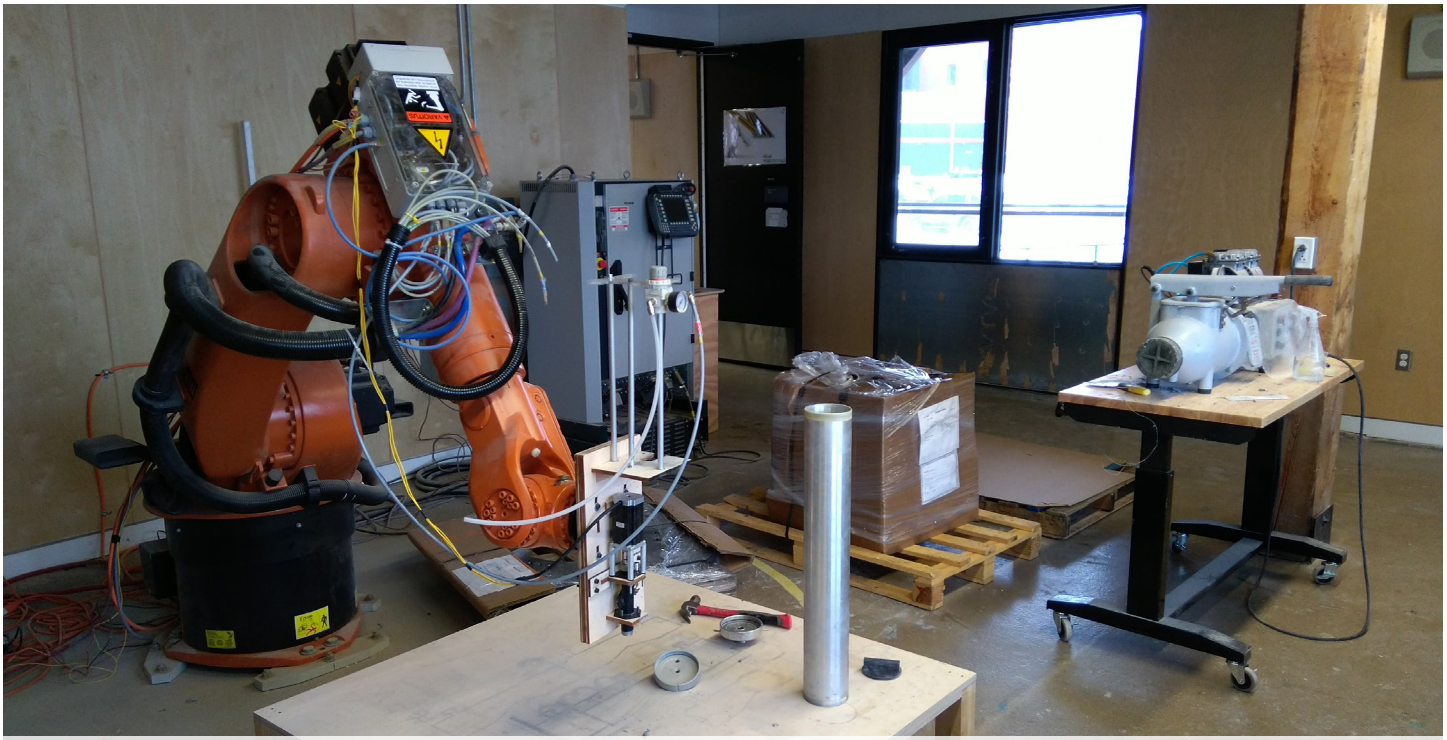


Figure 1. Image shows the Kuka robot, our primary tool throughout the project. Photo by Authors

For our 2nd year Masters seminar Abstract Machines: Artificial Intelligence and Robotics in Architecture we were tasked with investigating the possibilities provided by robotics (specifically the Kuka robot) in order to develop an integrated as well as performative system, in the form of a pavilion or facade.

Our class was presented with two material buildings systems of interest: Ceramic, as well as dowel laminated timber (DLT). From there, we were introduced to each systems possibilities, as well as projects around the world that have been innovative using these systems. This lead us to our investigation, which included looking at advantages and performative behaviour of each material, advanced manufacturing techniques, as well as possibilities of combining the two materials into an integrated hybrid system.

Our group primarily focused on ceramic, specifically the possibilities of 3D printing ceramic using the Kuka along with a grasshopper script developed by our professor in order to create modules that could be aggregated into forming a non-traditional brick component that could compose our design. A tutorial in operating the robot to 3D print, as well as test prints were integral in our understanding of the possibilities and limitations presented from 3D printing ceramic.

After establishing a general concept as well as our performative objectives for our wall assembly, our group went through several iterations, learning along the way in order to develop our final iteration, which moves and collects water along the surface of a facade, directing it to select areas of integrated greenery.

Figure 2. Image shows the Kuka robot, as well as the pug mill used for the clay. Photo by Authors

Background

Figure 3. Our project was inspired by geometric patterns seen in nature[2].

Inspired by Nature

Figure 4. Shows the geometry of the Fibonacci sequence in a shell[3].

Since the project involved the material exploration of two organic materials, wood (DLT) and clay (ceramics) through sustainable applications, it seemed fitting to have our design concepts inspired by nature. We wanted our structures to be informed by natural mathematical patterns inherently found in nature. This notion of rationalizing knowledge of the world through patterns was introduced by the works of D'Arcy Thompson, specifically that of his published work 'On Growth and Form' in 1917 which pioneered the use of mathematics in biology[5]. By utilizing patterns of biology and mathematics found in nature, our design explorations incorporate natural materials to generate a smart, performative facade system.

More specifically, design models using parametric design and biomimicry were instrumental in the development of our design. Parametric design allowed us to use mathematical parameters to inform and manipulate the relationships between elements to create an algorithm that can informed more complex geometries and structures, than we would have otherwise been able to achieve.

Biomimicry is the imitation of biological entities, geometries, and systems to inform the design and production of materials, structures and systems[6]. When both design models are integrated into a cohesive design approach, complex geometries and forms can be produced through algorithmic parameters to achieve architecture and systems that are intuitive with their surrounding environments. This was the basis for our facade design, specifically how natural patterns and systems found in nature

Figure 5. Image shows the Equiangular Spiral in Nature[4].

could inform the design of a parametric wall assembly that could perform sustainably with its environment. More specifically, we looked at two mathematical formulas, the Fibonacci sequence and the Equiangular spiral.

The Fibonacci sequence and the Equiangular Spiral, were utilized to inform the aggregation of wall modules to achieve an overall parametric wall assembly. Mathematically, the Fibonacci sequence is a series of numbers in which every succeeding number equates to the sum of the previous two numbers, e.g. 1, 1, 2, 3, 5..etc[7]. The equiangular spiral is an algorithmic spiral that evolves anti-clockwise where the length of the radii gradually increases[8].These mathematical equations can be seen in nature, such as plant formations, leaf structures and petal arrangements.

Throughout Thompson's research surrounding mathematical patters in nature, he had produced concepts of scientific growth patterns to explain and justify the inherent connections between organism growth and their resulting forms, pointing out that all changes of form are a phenomenon of growth[9]. Such patterns are expressed through Darwin's analysis of the logarithmic spiral which can be found throughout nature from shells to horns as demonstrated in Figure 4 and arrangements of leaves and other plant parts as demonstrated in Figure 5. This comprehension that the natural environment inherently consists of complex mathematical systems and patterns that enable natural systems to perform in a symbiotic and efficient manner is what has informed our design process.

Intentions

Figure 6. Greenery was important to our group, specifcally how it could improve the designs performance[10].

After determining that our overall concept was inspired by nature and natural forms, we began to think of different ways nature could be integrated within the design, rather than just inspiration for form. This brought us to the idea of incorporating greenery as well as water within our design in order to establish a self-sustaining system that could also add a performative element. We thought the incorporation of these two natural elements worked well with the overall concept we were trying to achieve while also providing an element of experimentation and innovation. Considering we found very few examples of existing projects that have incorporated all these elements, we had to begin to think though what was actually feasible.

Greenery

When our group first started our project, we were all intrigued with the idea of developing a green system that could begin to incorporate vegetation, throughout the design. Part of this was due to our interest in green infrastructure, however, a more significant reason for wanting to integrate vegetation was due to the performance aspect of a green facade. One of the primary ways green facades provide added performance to a building or facade is due to their ability to reduce a buildings heat gain during the summer, reducing mechanical demand to cool buildings. The reason for this is because most of the suns radiant heat is absorbed by materials with a greater solar mass, such as

Figure 7. In order to reduce the maintenance of the greenery, we wanted to be able to harvest and direct water[11].

concrete. However, vegetation on the exterior of a facade transfers the suns heat 20-40% through evapotranspiration, 5-20% through the plants photosynthesis, 5-30% the vegetation reflects, leaving a smaller portion of the heat to be absorbed by the building mass[12]. As a result of these aesthetic and performative aspects, our group felt it was an important component to integrate within our final design.

Water

Considering that our group wanted to integrate vegetation within the design, an important question came up "how are we going to water the plants?"

Since a lot of green infrastructure, specifically ones with more individual planters, require a large amount of maintenance, we wanted to design our facade in a way that needed a minimum amount of maintenance, specifically watering the facade. In order to do this, our group came up with the idea of designing a facade that could capture rainwater, and direct it towards strategically placed planters along the surface of the facade. Although this was the intention of the project, we initially did not have a clear idea of how we wanted to achieve this end goal and wanted to let our test prints inform us what was possible so we could conceive a design that was both performative, aesthetic and feasible.

Case Studies

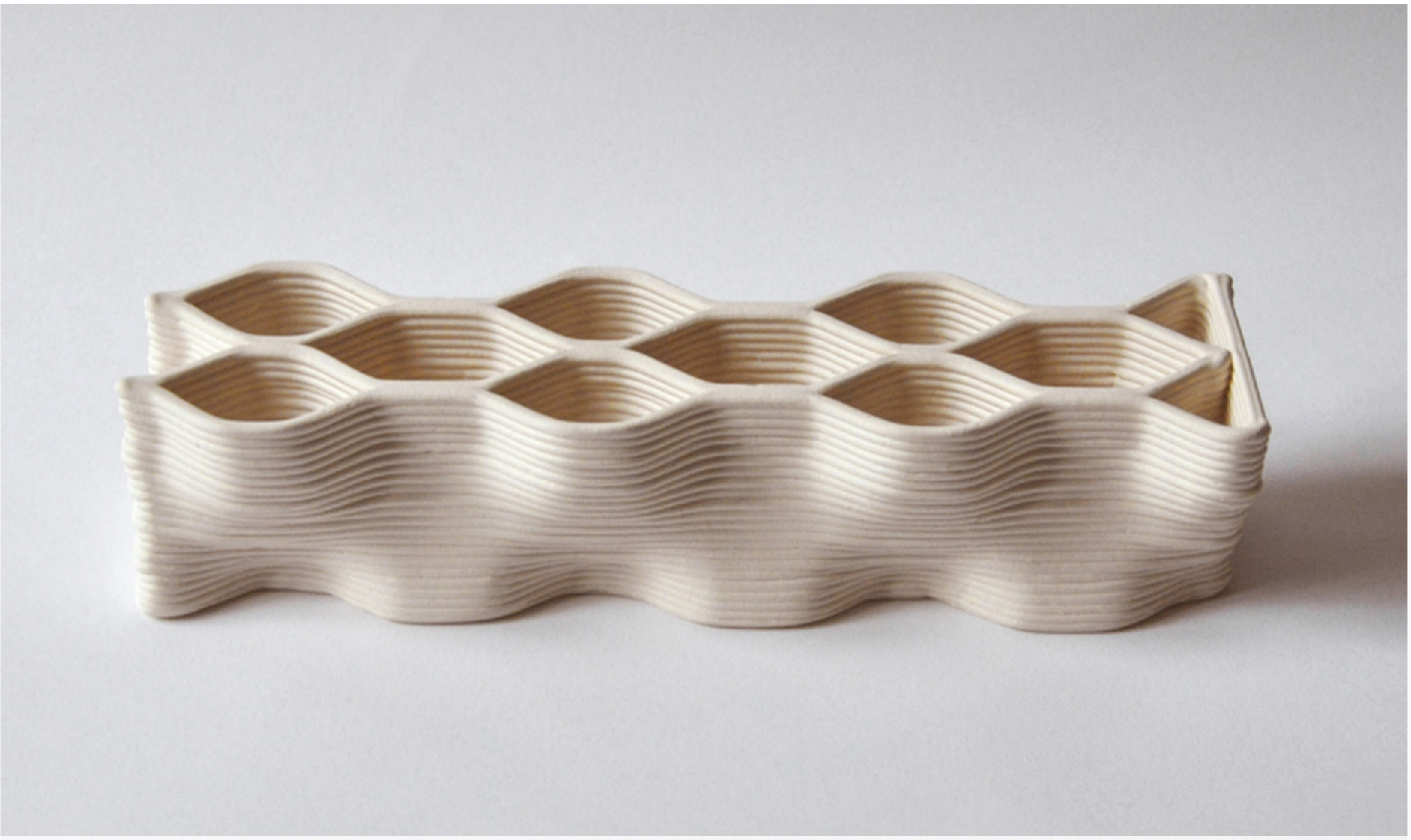


Figure 8. Building Bytes by Brian Peters is a 3D printed design that can aggregate in 2 directions[13].

Building Bytes
By: Brian Peters

Created by architect Brian Peters, he adapted his desk 3D printer to print ceramics and produce intricate bricks for architectural applications. His intention with this exploration was that the introduction of 3D printers to the world of full-scale architecture could create a series of portable brick factories. This new production system could use concrete or other materials as well, and it makes for a more flexible design methodology of on-site troubleshooting and customization for different situations. He used two approaches, the first (shown above) was to create a uniform brick structure to be aggregated in a set fashion, or a complex overall form made of individually unique bricks[15].

The design provided our group with a flexible aggregation strategy that creates a different effect depending on how it is installed, while removing the need for any mortar due to its interlocking geometry. This inspired us to explore a simple repeatable internal structure to potentially collect and direct water or as a grid to allow for connection between the individual bricks

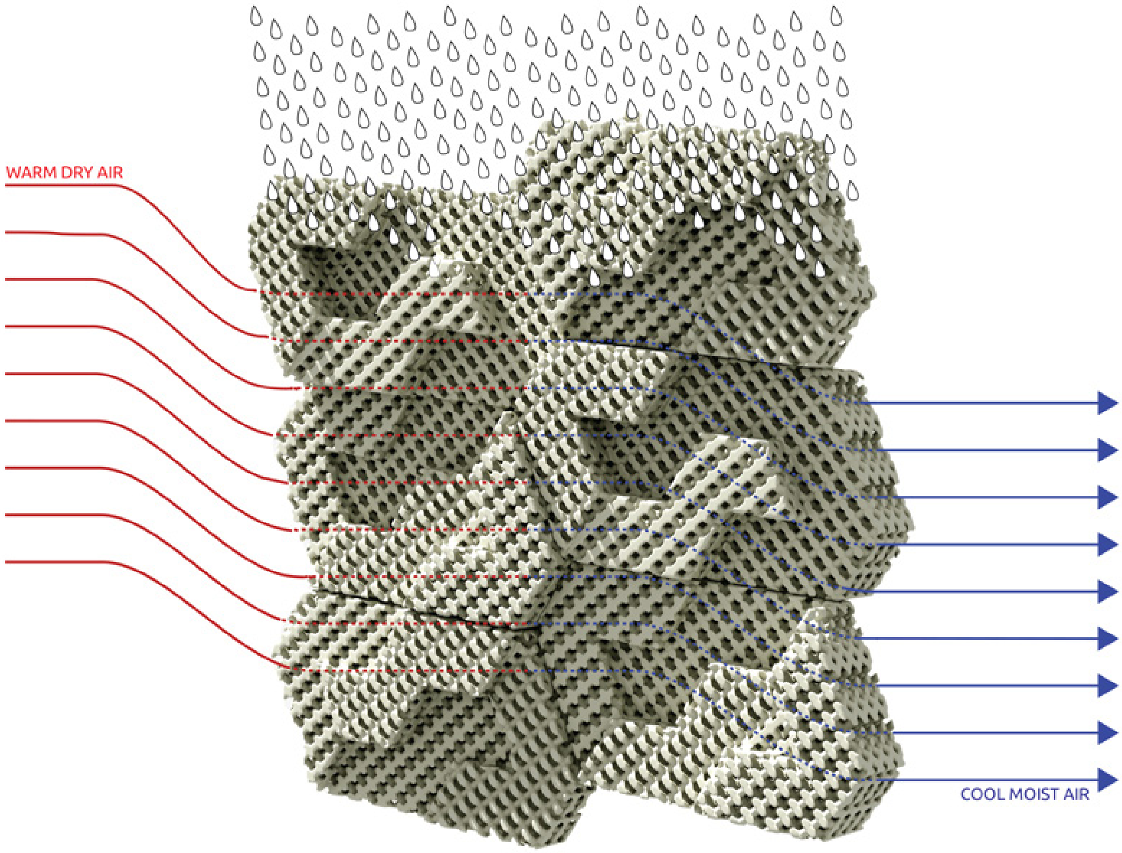


Figure 9. The Cool Brick utilizes the principles of evaporative cooling to cool air as it passes through the wall[14].

Cool Brick
By: Emerging Objects

The Cool Brick by Emerging Objects are bricks that are 3D printed out of porous ceramic and are set in mortar. Each brick absorbs water and is designed as a lattice that allows air to pass through the wall. When air moves through the porous brick, the water that is held in the ceramic evaporates, cooling the air on the interior environment, using the principle of evaporative cooling.

The bricks are modular and interlock by stacking to make a screen. Additionally, the shape of the brick creates a shaded surface to keep a large portion of the wall's surface cool and protected from the sun, improving performance. As a result, the Cool Brick system is used to build walls in order to passively cool interiors in hot environments[16].

The Cool Brick is a very interesting case study because it is able to achieve a form that can capture and store water for the purpose of evaporative cooling. It also shows how a module can begin to aggregate vertically and horizontally, while establishing a form that actually begins to shade itself to improve its performance.

Figure 10. Planter Brick by Emerging Objects is a module that incorporates vegetation to reduce heat gain[17].

Planter Brick
By: Emerging Objects

The Planter Bricks by design firm Emerging Objects are uniquely designed concrete units that hold vegetation. The planter bricks were designed in order to try and counter the heat island effect throughout cities, taking advantage of evapotranspiration and the conversion of pollution, using the plants to clean the air. The plants along the wall help mediate the temperature of the building, and help to establish a sound buffer, reducing the amount of outside noise that penetrates through the wall surface into the interior spaces.

The planter brick was intended to be combined with traditional masonry bricks in a new wall or to replace bricks in an existing wall. The brick comes in a variety of forms, some are angular, while others are curvilinear, while featuring various sized cavities for vegetation[19].

This brick helped our group think about how we could begin to incorporate vegetation within a standard brick sized module. However, this module did not address connections horizontally or vertically between modules, and did not consider the movement of water.

Figure 11. Planter Tile by Emerging Objects incorporates vegetation, using a hexagonal locking module[18].

Planter Tile
By: Emerging Objects

The Planter Tile by design firm Emerging Objects are 3D printed cement hexagon tiles that aggregate and lock together. The overall pattern is composed of 6 different patterns, 4 of which are able to host different forms of vegetation. The design of the tiles is based off of a petal motif, tying together the planter tiles and non-planter tiles through the use of common graphics in order to achieve a harmonious facade. However, due to the material process involved in making the tiles, the tiles show an uneven coloring which creates varying hues and adds a sense of individuality of each tile[20].

This brick was an important case study because it helped our group think of non-traditional shapes that could begin to be aggregated as a brick module and locked into place, rather than just stacked. Additionally, it provided our group with another possible way of incorporating the planters into the wall design, establishing unique pieces that can then as a whole begin to create an overall layout that looks harmonious.

Methods

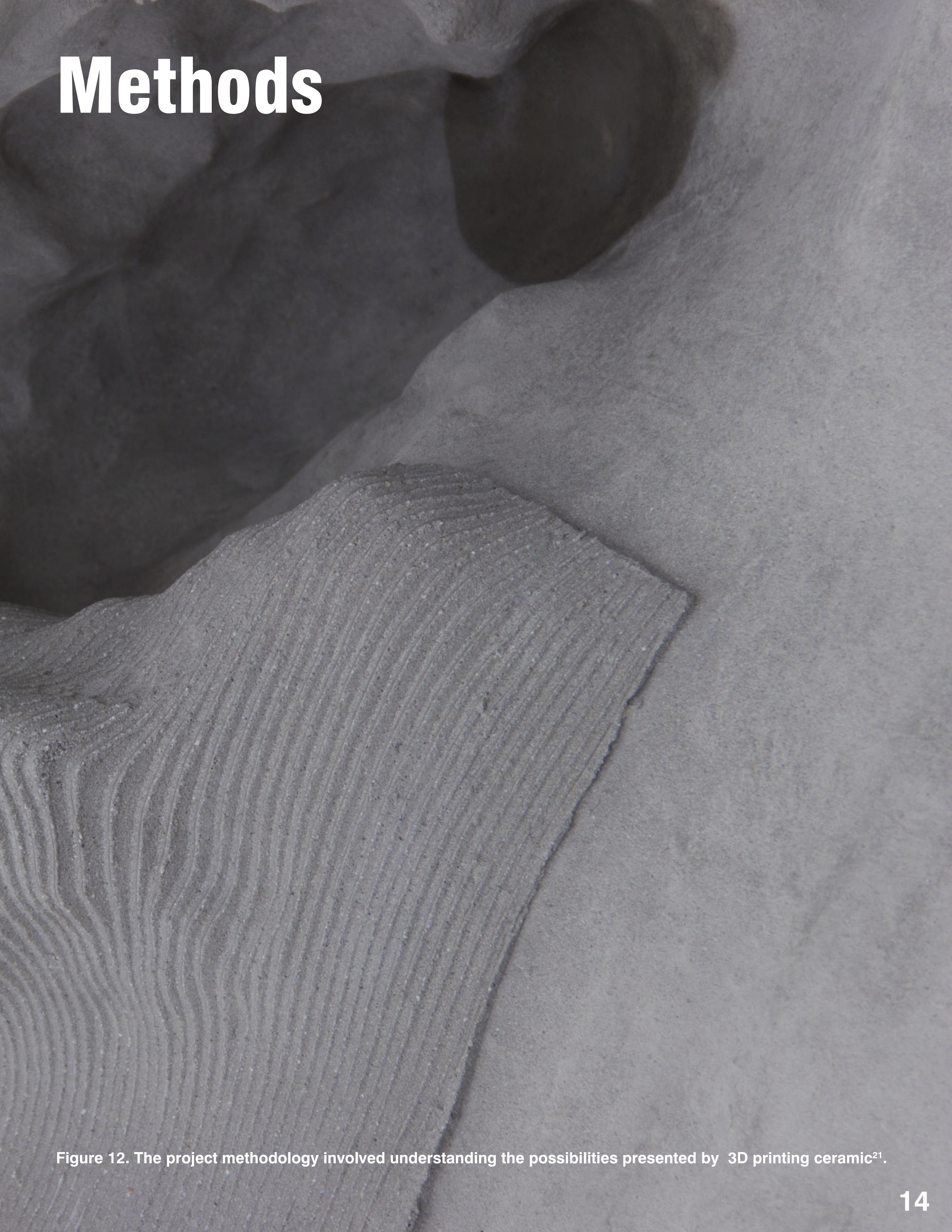


Figure 12. The project methodology involved understanding the possibilities presented by 3D printing ceramic[21].

Material Investigation

Figure 13. Considering DLT was one system we investigated we completed a material investigation into timber[22].

Wood

Considering Sudbury is located in the boreal forest region of Canada, we are surrounded by an abundant variation of tree species. From softwood such as black and white spruce, jack pine, balsam fir, tamarack and eastern white cedar to Hardwoods like the poplar and yellow birch[24]. Therefore, we are able to tap into this natural resource in order to provide construction methodologies that have ecological principles as a core foundation. In regards to a fabrication process, we can begin to apply the Kuka robotic arm as a way to precisely subtract material in order to achieve complicated forms which can then be assembled into a potential pavillion. This can include things like drilling precise holes in order to make custom DLT assemblies. Unlike the additive nature of clay, the building methodology regarding wood would be subtractive.

Figure 14. Clay was a important material for us to understand because we were primarily 3D printing ceramic[23].

Clay

Clay is a naturally abundant soil particle of less than 0.005mm. It is an important component for the agricultural industry, as it proves itself suitable for plant growth. Yet it is also used in a variety of building processes from pottery to adobe bricks[25]. The process of working clay into form leaves the material in a fragile state. In Northern Ontario, we are located within the clay belt which is a region that covers 16 000 000 acres which is shared with Temiskaming abitibi in Quebec[26]. This means that we are located among a naturally abundant source of clay. The process of firing is used in order to solidify the product from ceramic toilet bowls and more. The material suits itself to be 3d printed as the pre-fired state of the material is soft enough to be extruded in a pressurized canister. This method can be viewed as an additive methodology. As such, the kuka robot equipped with the proper tools, means that we can combine digital fabrication techniques with clay be it local or otherwise.

Parametric Design

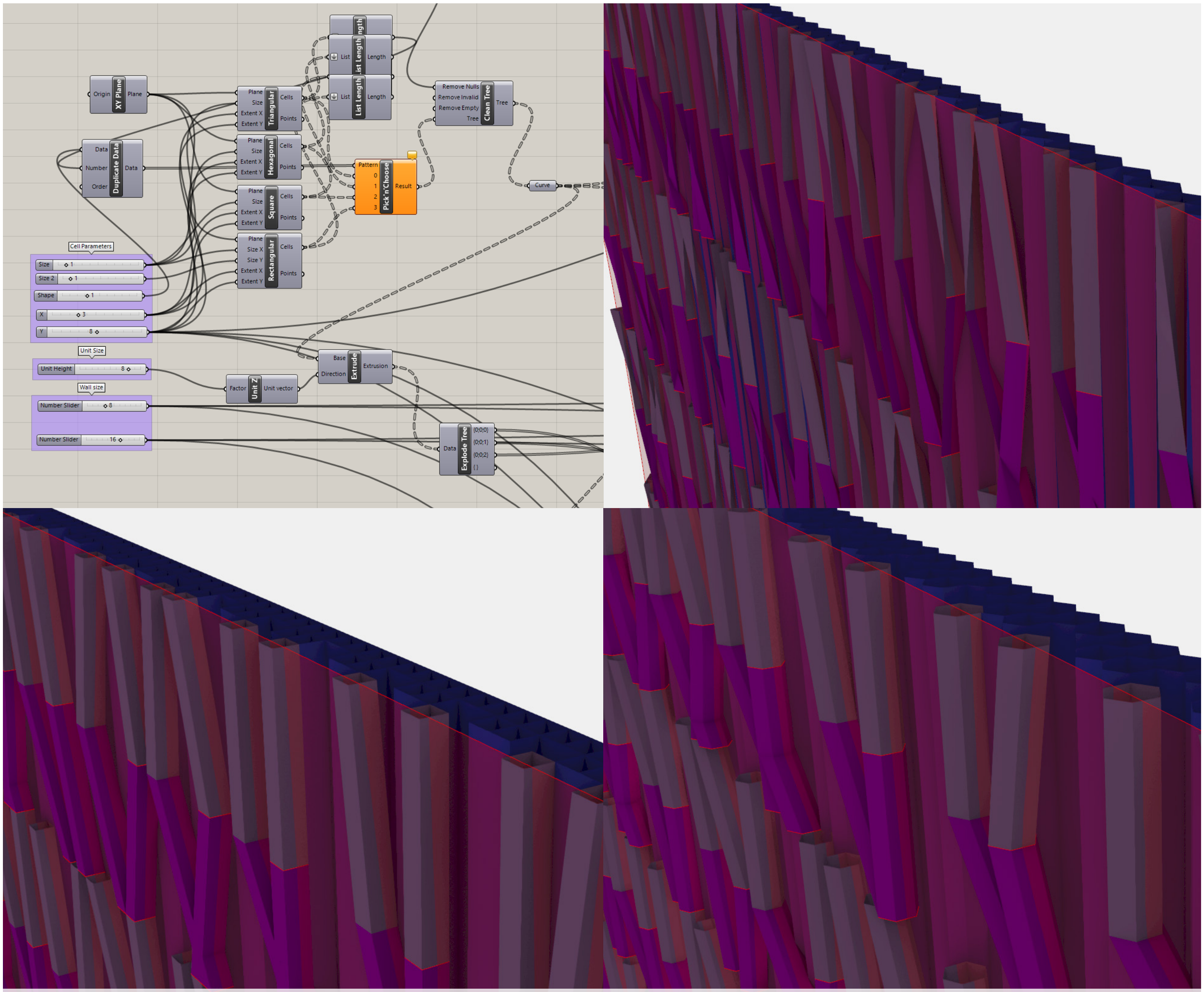


Figure 15. The grasshopper script allowed for various shape iterations of our modules. Photos By Authors

Our groups initial parametric exploration led to the investigation of the golden ratio and the use of randomness. The utilization of grasshopper meant that we were able to set up parameters that would allow us to quickly filter through various design options. In our attempts to create a modular design. We opted for the use of three layers of geometry that would be interconnected as to perform different tasks. In the grasshopper definition, we were able to quickly iterate between the base geometry such as triangular, rectangular, hexagonal or square. These shapes would then form the brick which could vary in length, height and thickness depending on the sliders that defined them. From this, the ability to create an array of bricks was fairly simple keeping in mind that we would utilize trees in order to further modify the performative nature of the internal and external layers that we had created for ourselves.

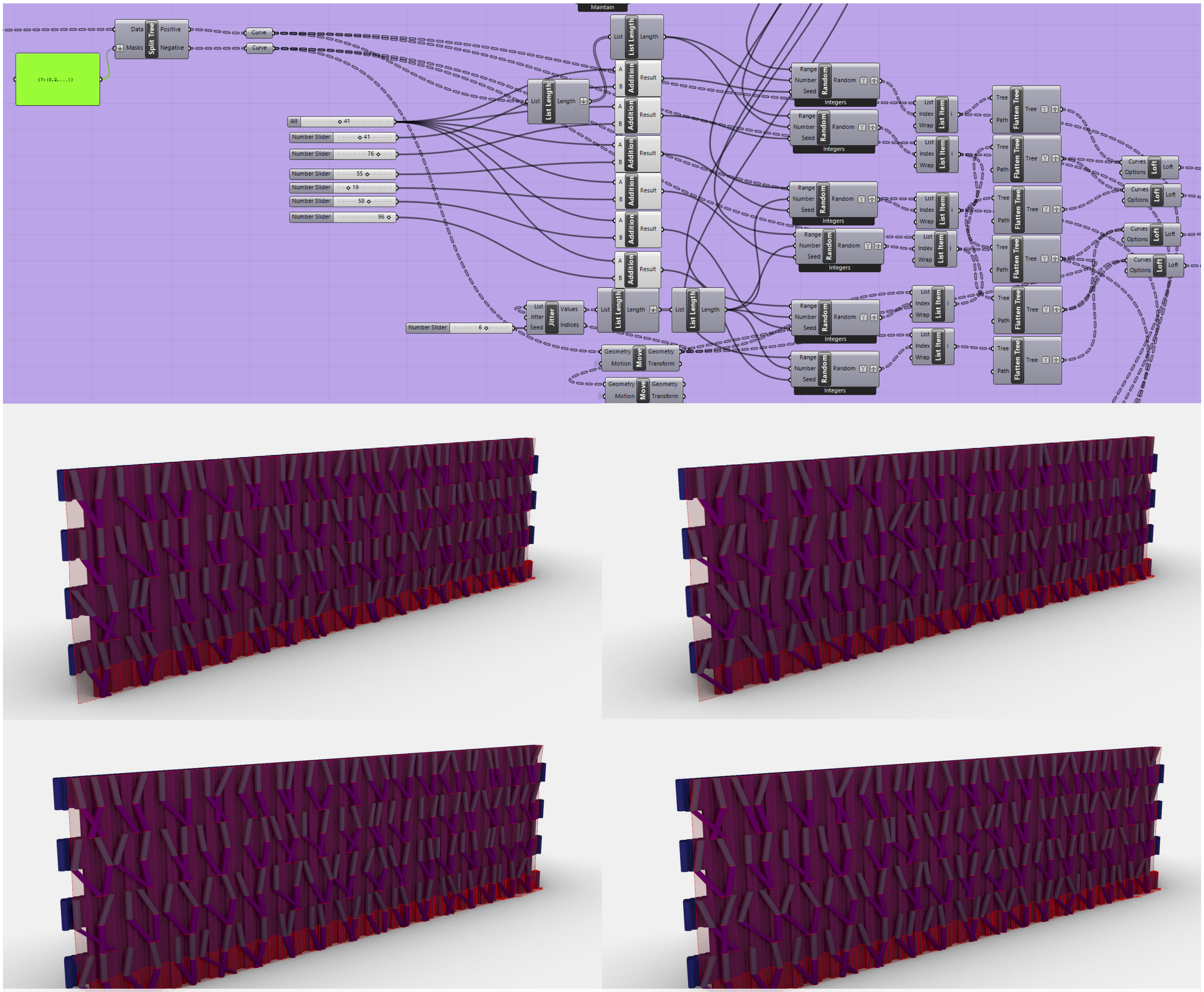


Figure 16. The grasshopper script and variations showing the randomized modules. Photos by Authors

The use of the Fibonacci and random component were used to experiment with the order upon which the exterior water channels were arranged. The fibonacci relationship simply suited an aesthetic purpose through the design. On the other hand, the randomness was used to control the flow of water through countless variations. The key to this method was to maintain the tubes within a brick unit. Otherwise the wall would not be able to be printed with the robot. Unfortunately, this design approach was only taken so far because it did not align itself with the skill set of the majority of the group, and we found ourselves to be restricted design wise by the parametric component.

Graph Mapper

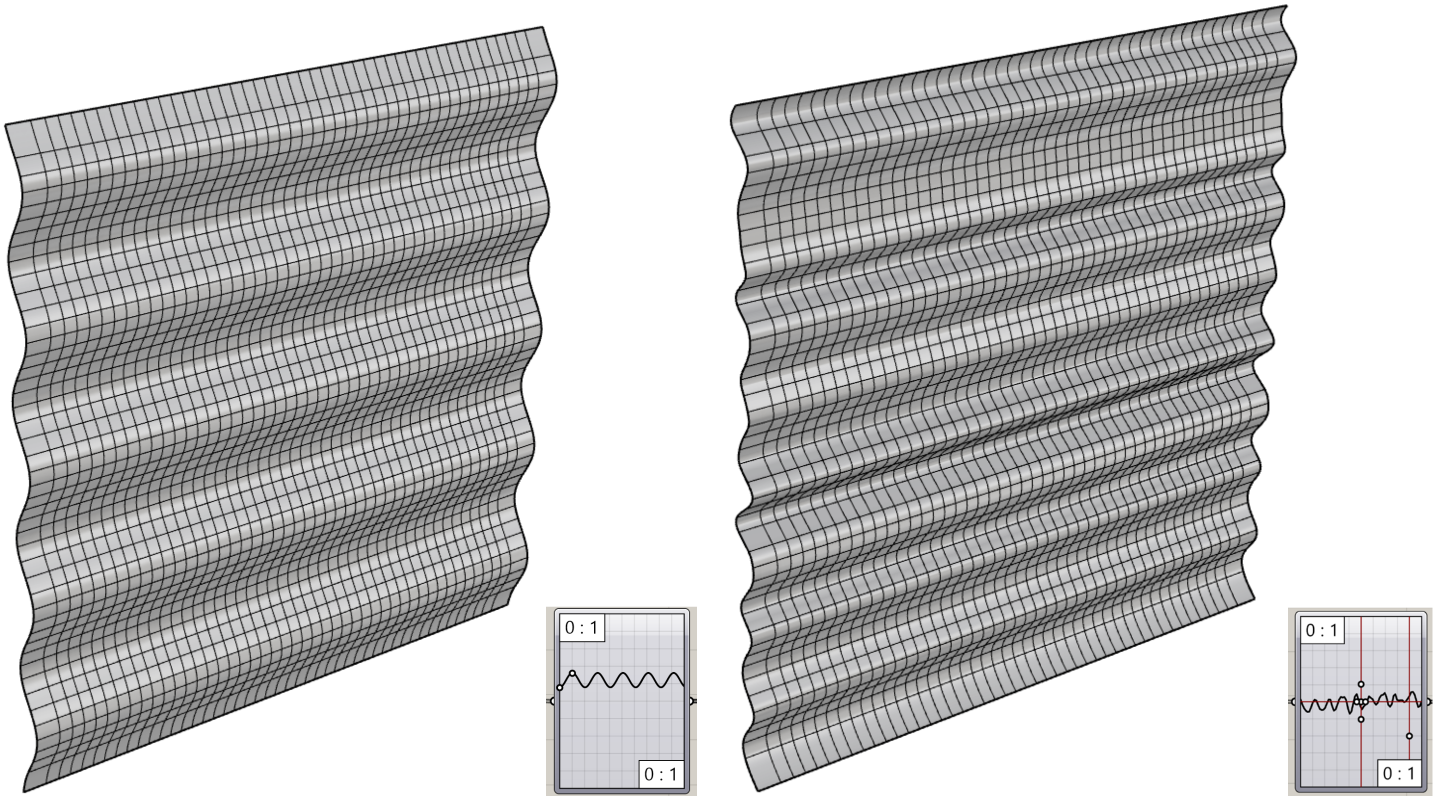


Figure 17. Two different variations using the graph mapper to create an exterior form. Photos by Authors

Another component of Parametric our group explored were the possibilities presented by the graph mapper operation within grasshopper. Considering that our group was initially inspired by mathematical formulas such as the Fibonacci sequence in order to determine form, this seemed like a worthwhile investigation. The graph mapper allowed us to use standard graph formulas such as sin waves in order to establish the exterior form that would be applied to the standard back end of our wall assembly. The mapper allowed for many different iterations with a high level of control because we were able to control the frequency of the waves as well as the magnitude of each.

As a result, we recreated the standard rectilinear back end of our assembly, and used the bounding box to reference where the map would be applied to, allowing us to try different mathematic curvatures to determine our exterior form.

While this was a worthwhile investigation our group felt the graph mapper was too standard in how it created the waves. We wanted a more curvilinear design that curved in multiple directions all at once, in order to create a more aesthetically interesting facade, but also allowed us to imagine how the water would be directed to planters.

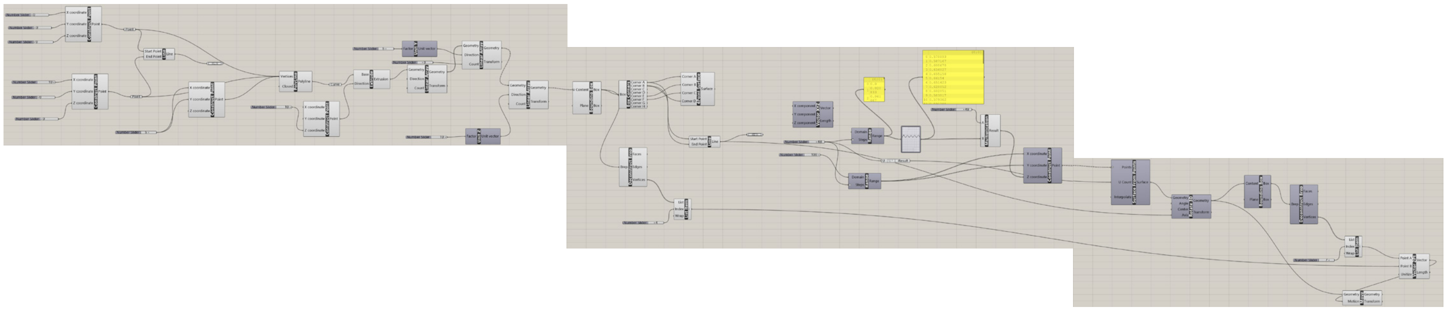


Figure 18. Graph Mapper Script. Photo by Authors

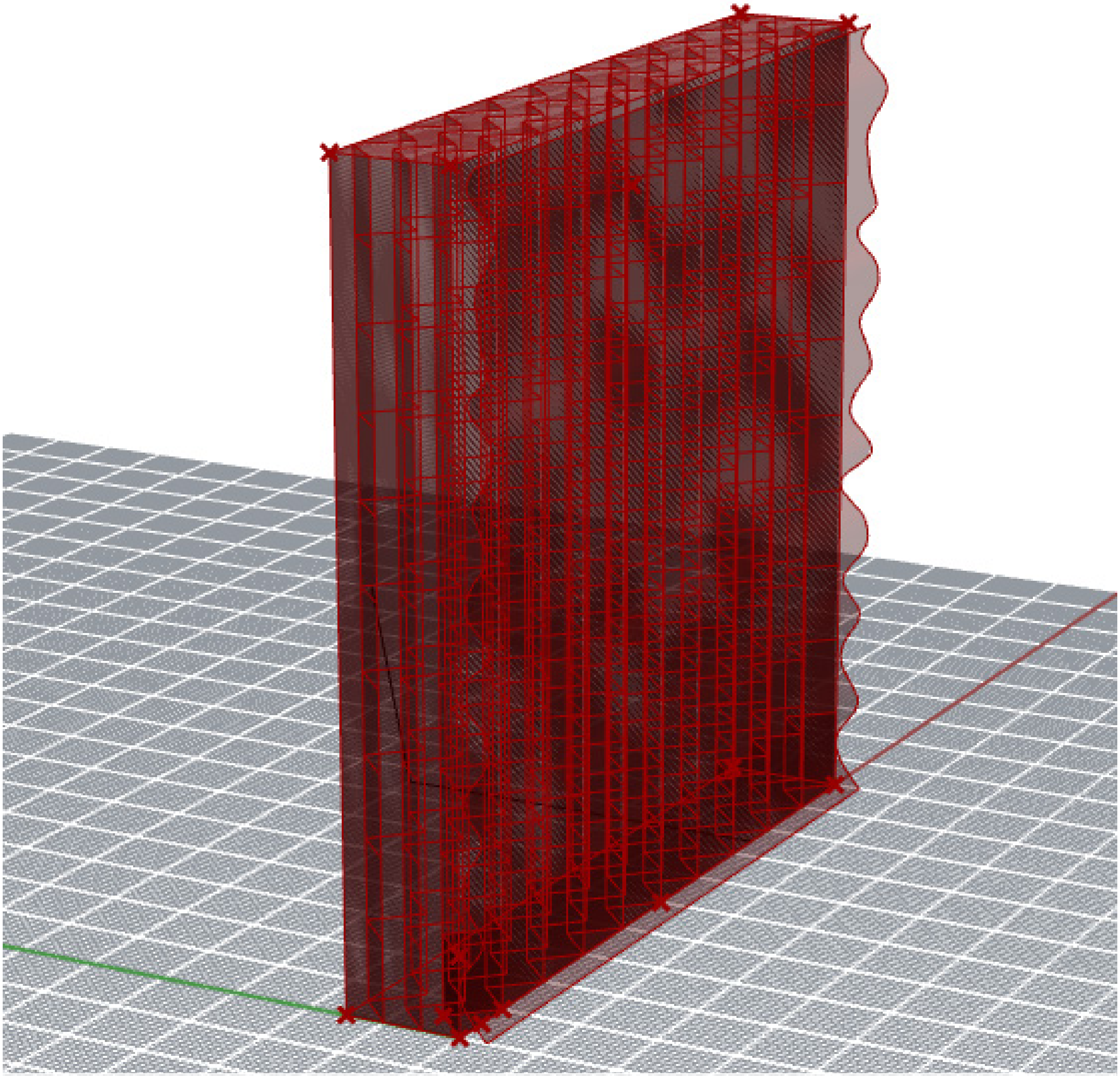
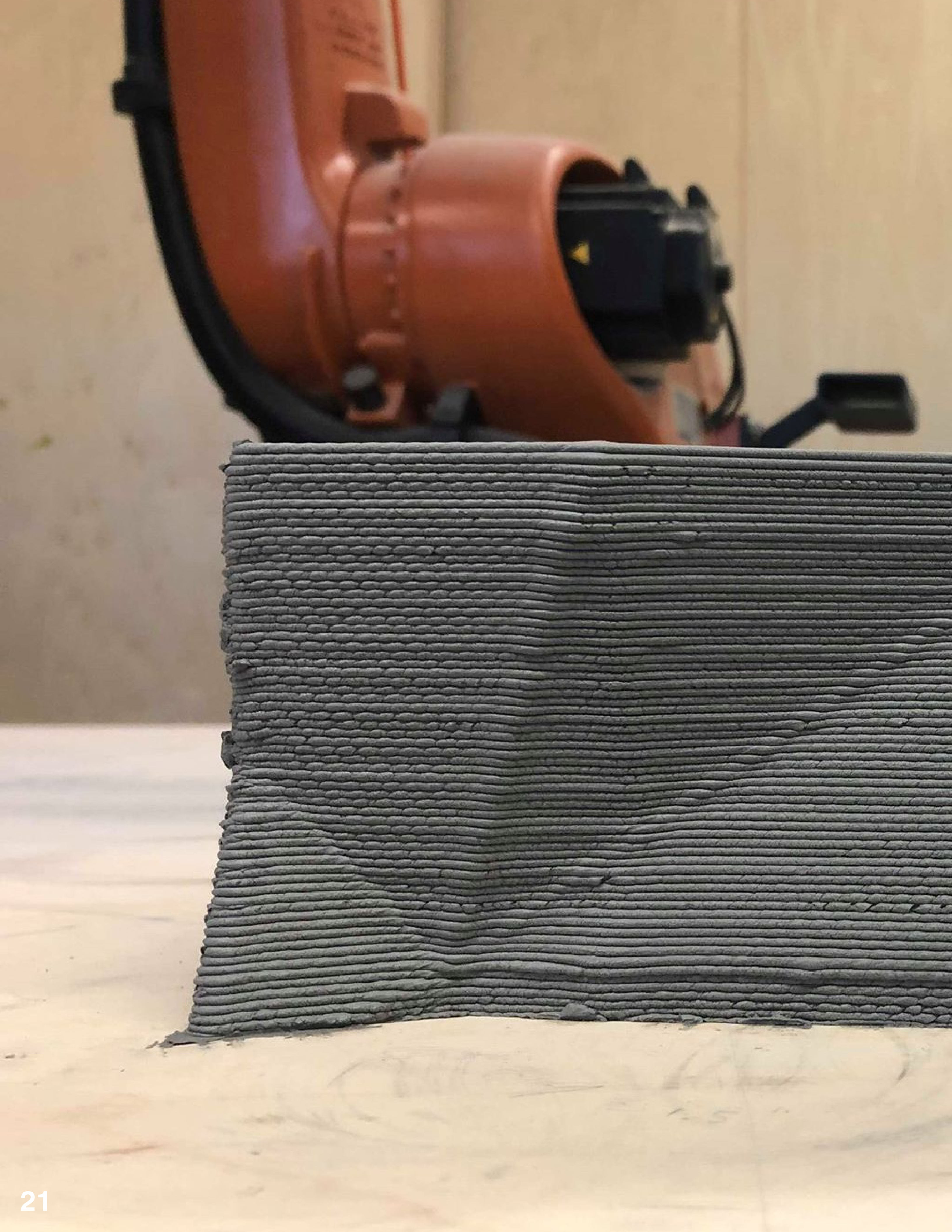


Figure 19. The graph mapper was applied to our wall structure using a bounding box. Photo by Authors



Testing

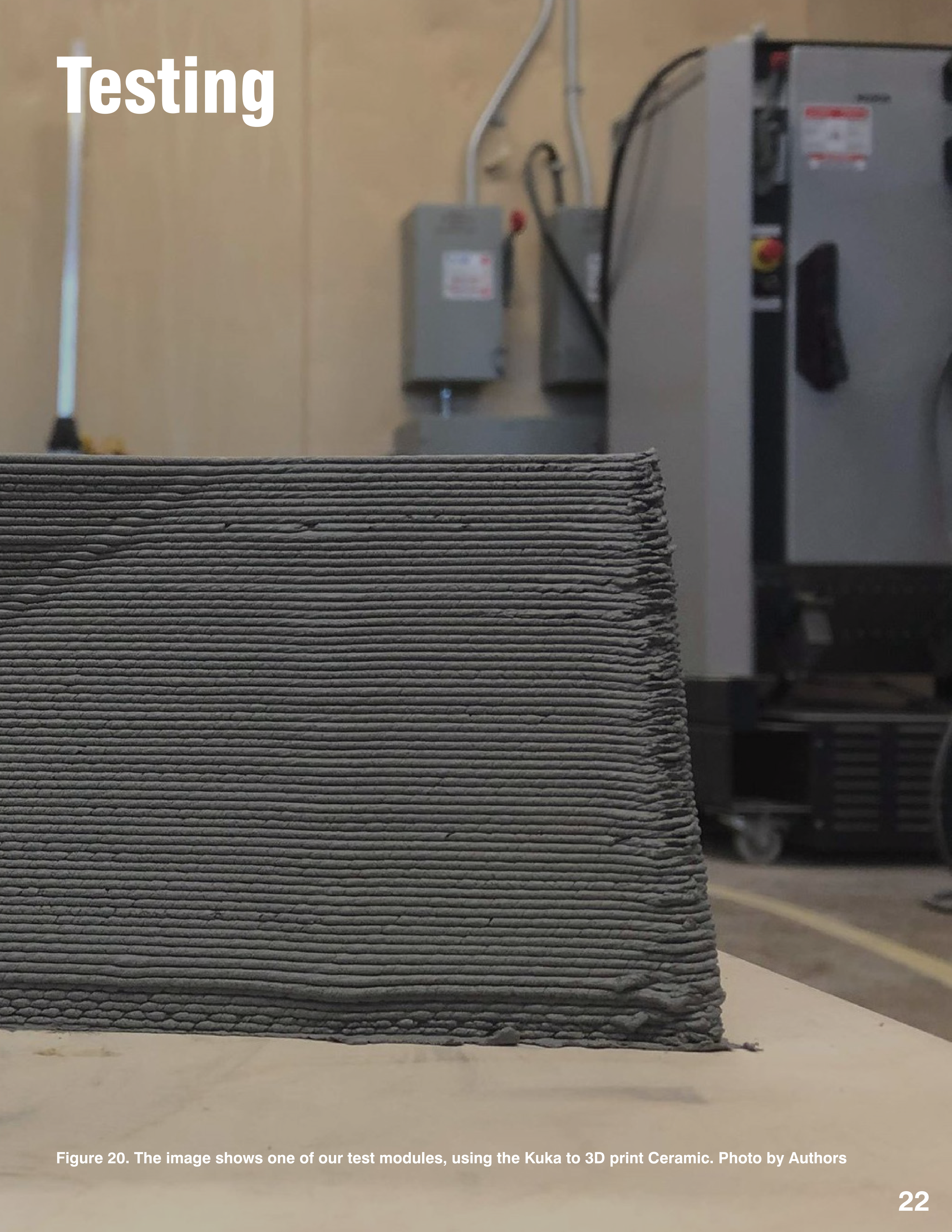


Figure 20. The image shows one of our test modules, using the Kuka to 3D print Ceramic. Photo by Authors

Pavilion Concept #1

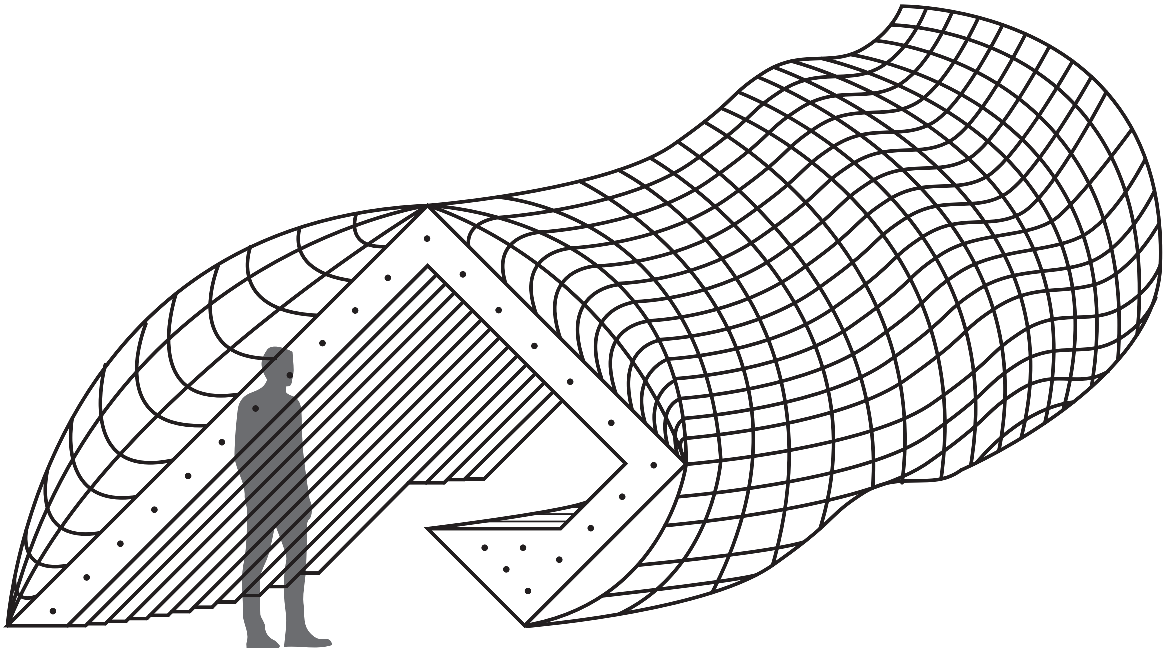


Figure 21. One of our initial concept pavillions. Image by Authors

Initially, our design exploration of integrating DLT and ceramic was focused around the design of a pavilion. The intent of the pavilion was to create a structure that was inspired by inherent patterns found in nature, and be informed through mathematical patterns found through the Fibonacci sequence and the Equiangular spiral. By incorporating both fabrication technologies in a cohesive manner an aesthetically interesting architectural intervention could be achieved. Creating a structure that can mitigate and collect rain water through the rigid formation of the wooden DLT structure coupled with the organic forms of the aggregated ceramic planters.

As a group, each member individually produced a design proposal for the pavilion from which its form, design concept and performative qualities were to be inspired by the Fibonacci sequence or the Equiangular spiral. The document will showcase the conceptual design proposals that were produced demonstrating several interpretations of the groups' overall initial design concepts.

This design concept was inspired by the Fibonacci Sequence, and was a very literal translation in order to form the sectional form of the pavilion. Beginning with the sequence, a material thickness was applied (2x4). From there this surface was extruded to create an enclosure. However, this was relatively straight forward and not interesting enough. As a result, a new curve was established so the timber members would undulate through staggering, mimicking a wave pattern. From there an overall curvilinear form was established for the pavilion. A grid was established and mapped onto this surface in order to inform the ceramic planters that would incase the pavilion providing a juxtaposition between the lumber rectilinear interior and the ceramic curvilinear exterior. While initially this was a concept of interest, it was a much too literal translation of the Fibonacci sequence and the ceramic to DLT connection was very unresolved.

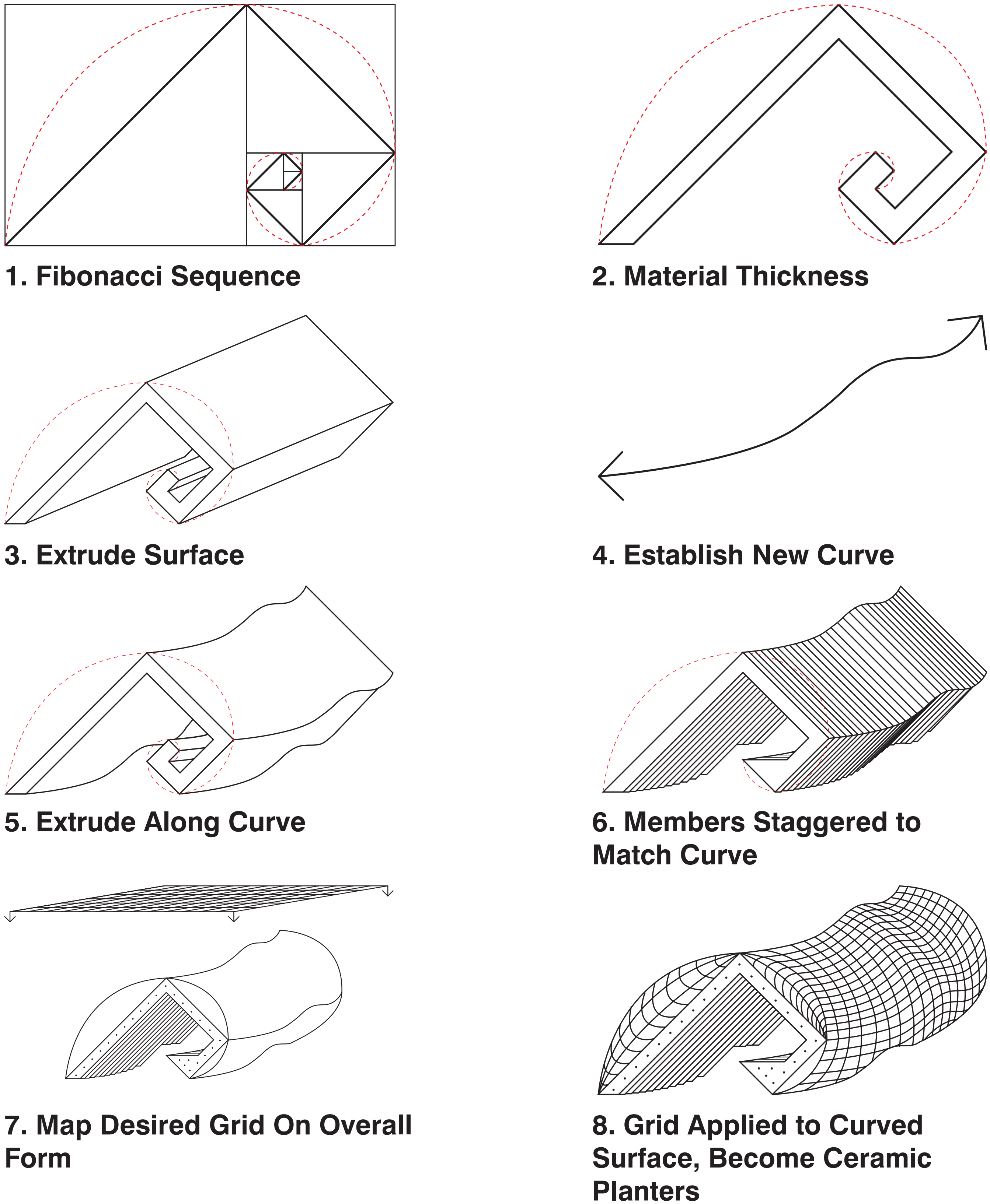


Figure 22. Diagram explaining the process imagined to achieve pavillion. Photo by Authors

Pavilion Concept #2

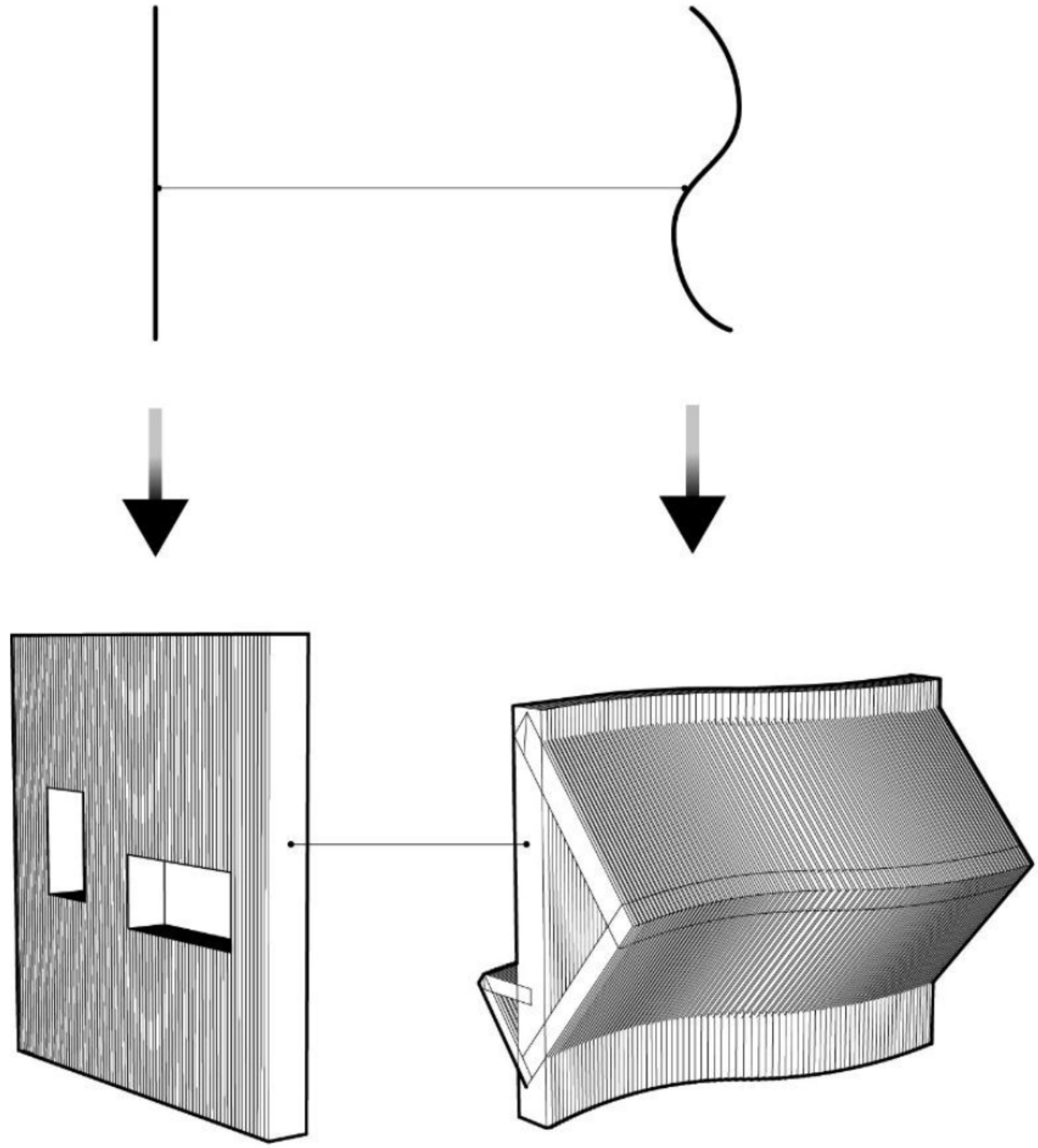


Figure 23. Conceptual inpiration for DLT wall assembly. Photo by Authors

An early attempt at finding an interesting frame to apply a ceramic facade to, this concept shows a potential adaptation of DLT that would produce different types of connection between the structure and its cladding. This idea was abandoned for a more straightforward design due to its complexity and a more rigorous focus on the ceramic aspect. We decided to just use the flat DLT as a structural element and apply more thought to the interlocking of the bricks themselves leaving potential connection to the wall as an additional connection later. As a result, this was one of the tests that pushed our group to primarily focus on a ceramic facade rather than a hybrid system which would create a pavilion.

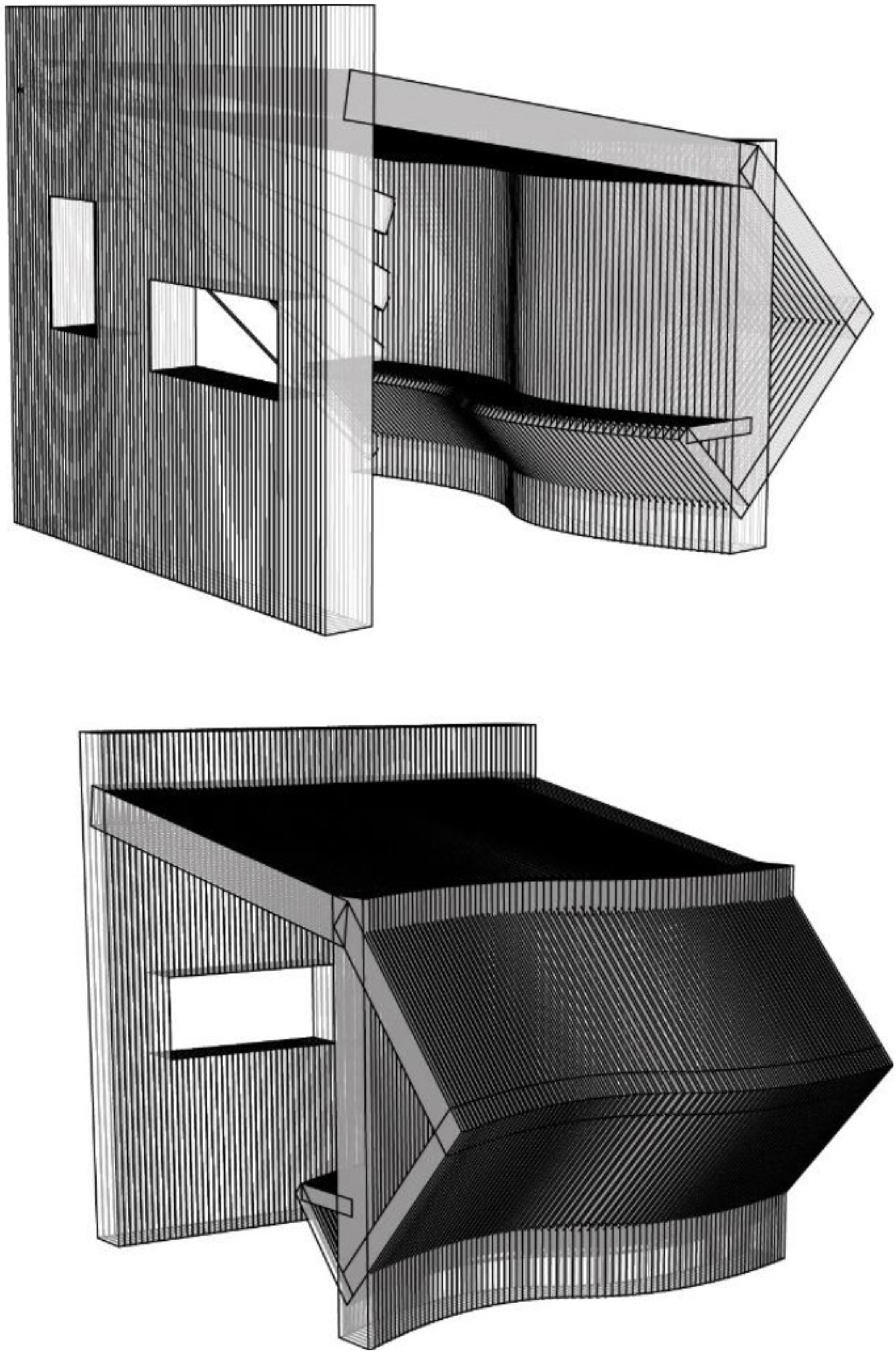
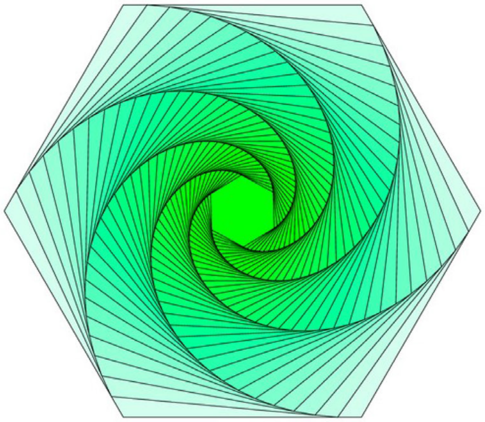
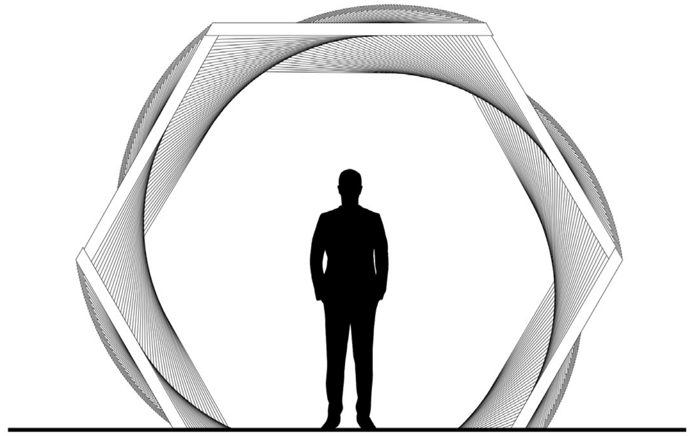


Figure 24. Line work elevations of proposed DLT concept. Photo by Authors

Pavilion Concept #3

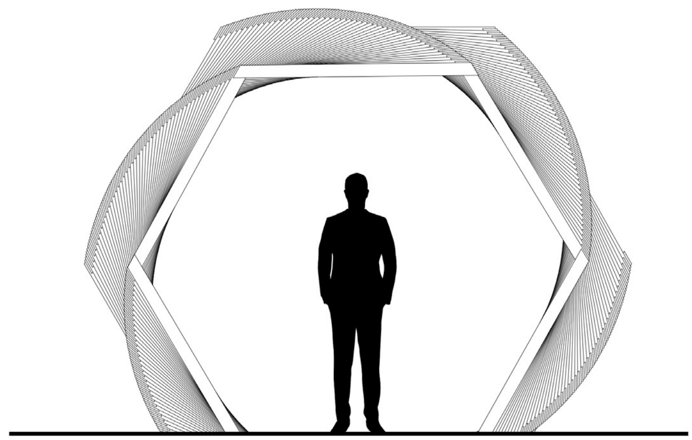


Euqiangular Spiral



Front View of Model

Euqiangular Spiral Found In Nature



Back View of Model

Figure 25. Image shows the relationship between the Equiangular Spiral and the pavilion. Photo by Authors

This pavilion concept explored how the equiangular spiral found throughout nature could be understood through the human experience of the pavilion. The pavilion was designed by arraying the geometric shape of a hexagon along a 14 foot path, where the geometry would progressively be rotated and decreased in size throughout its length. Eight hexagons were placed at two foot intervals from which they were rotated counter clockwise by 10 degrees. The lines of the geometric hexagons were then lofted to generate the rough form of the pavilion. This shape then informed the placements of where the offset 2’ x 6’ wood members were to be placed and dowel laminated.

Through designing the structure in this manner, the form of the pavilion mathematically followed and resembled the Equiangular Spiral through a physical extrusion of the hexagonal form. The outcome produced a pavilion that would allow the human experience of walking through the pavilion to understand how these mathematical patterns inherently inform structures found in nature. Additionally, the physical embodiment of the Equiangular Spiral allowed the rectilinear building system of DLT to achieve an organic formation. While allowing the structure to encourage informed water flow along its exterior surface, passively curating rainwater runoff.

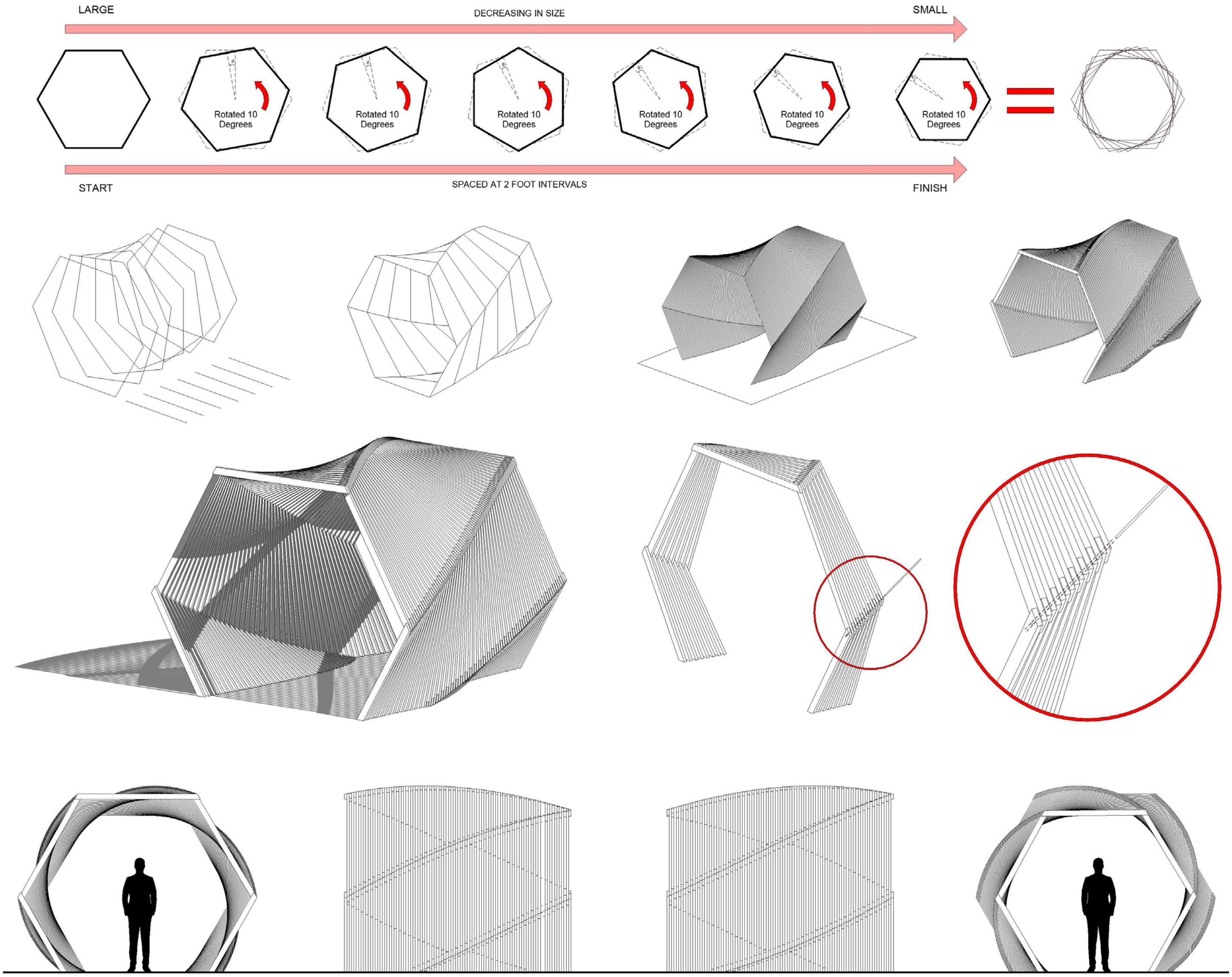


Figure 26. How through the rotation of a hexagon the Equiangular Spiral could be acheived. Photo by Authors

With the addition of a ceramic facade that could be mounted atop of the DLT structure, more organic forms could be achieved along its surface that could further direct rain water runoff while embedding planters with its composition that would be able to collect and mitigate the rainwater. Generating an aesthetically pleasing structure that could provoke how these building systems can be cohesively designed to perform intuitively with its surrounding environment. However, once again the integration of the two building systems was quite unresolved and seemed rather daunting.

As a result after this point our groups' focus shifted to working primarily with ceramic and ensuring we could make that portion work as a facade, rather than worrying about a more complicated hybrid that incorporated both different systems into a pavilion.

Test Print #1

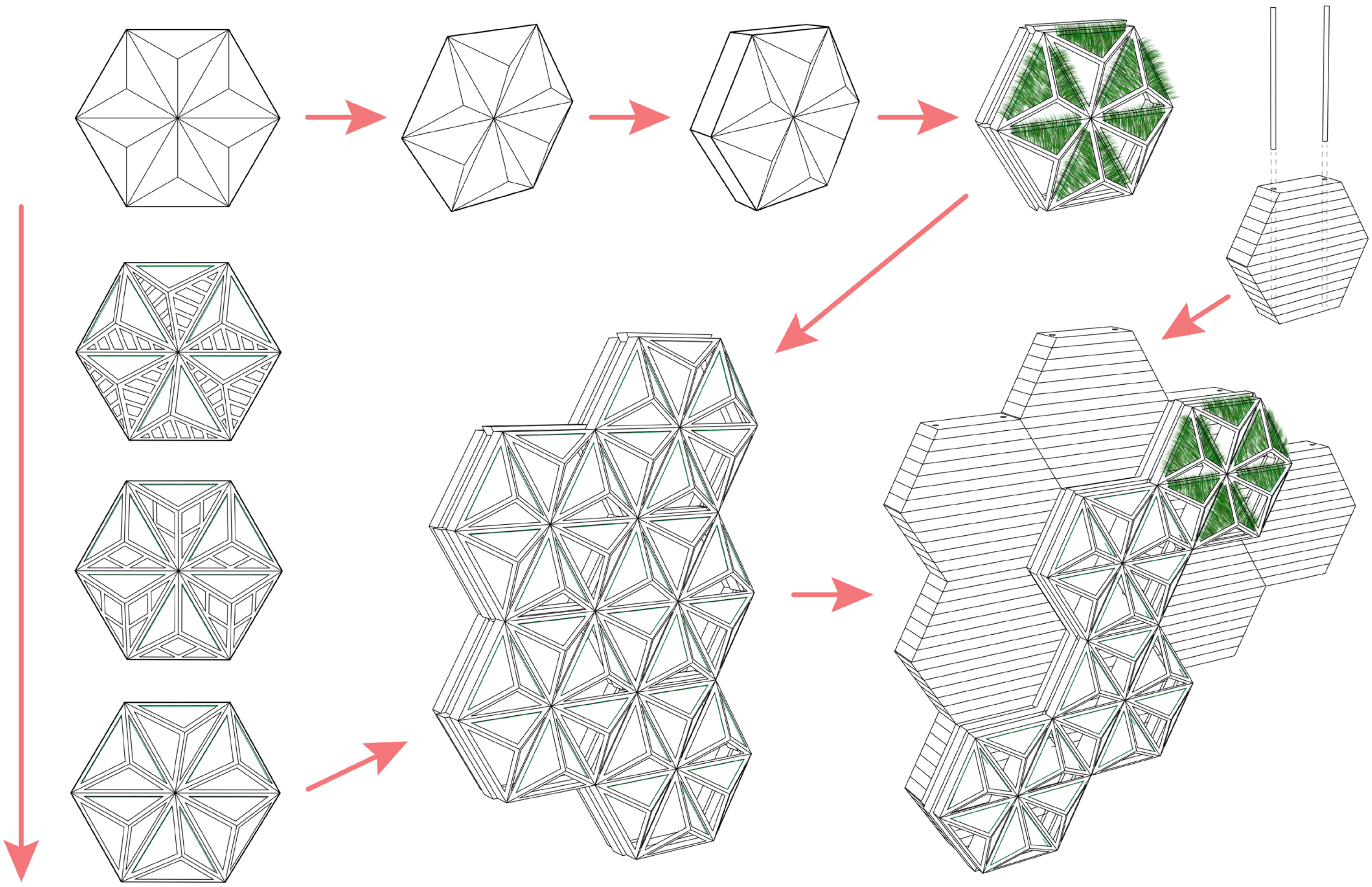


Figure 27. Diagram showing concept of hexagon planter tiles. Photo by Authors

After presenting our conceptual design proposals for a pavilion that integrated the two building systems, we decided to direct our focus towards exploring ceramics as a sustainable building system. As our design concept had pertained more towards developing a performative facade system rather than that of a DLT structural system. The intent moving forward was to develop performative ceramic wall modules that integrated several passive systems within each unit to create an overall cohesive and sustainable aggregated wall assembly. While still exploring how the ceramic wall and its modules could be fastened onto a DLT structural wall system.

The design iteration illustrated was the exploration of hexagonal modules that could be aggregated into an interconnected wall assembly. With our project being inspired by nature, utilizing inherent patterns and structures found in biology, the structure of the honeycomb informed the design development of this proposal. The geometry of the hexagon was subdivided into several triangulations from which six pyramids had formed the design of the facade for each modular unit. The vertical faces of the pyramids of each module was to be converted into planters where rainwater would be collected and mitigated. The second intent of the design was to have the underside faces of the

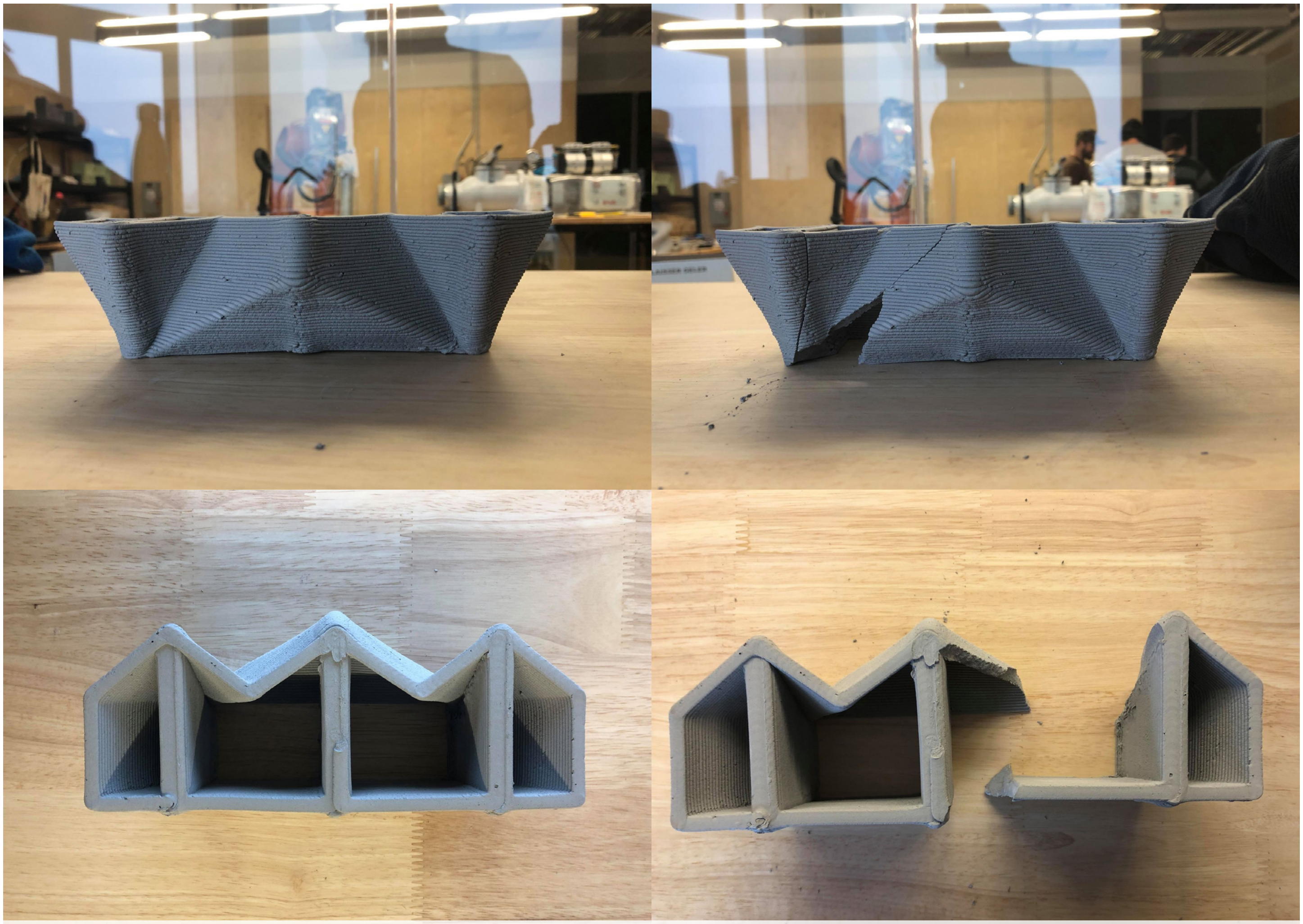


Figure 28. Our test module before and after strength test. Broke along seam. Image by Authors

pyramids to form window openings from which the planters would passively shade the window openings. Additionally, ideas were also proposed as to how the DLT wall assembly could be modularly designed to work with the aggregated hexagonal shape of the facade, allowing the aggregated nature of the design to extend the aggregation beyond the facade system.

Printing only 30% of the module, this facade design served as our first ceramic print. The print allowed us to test the cantilevered conditions that are attainable through ceramic printing. While allowing us to test its compressive strengths, concluding that the weakest contentions of the prints were where the structural support met the front face of the facade.

Test Print #2

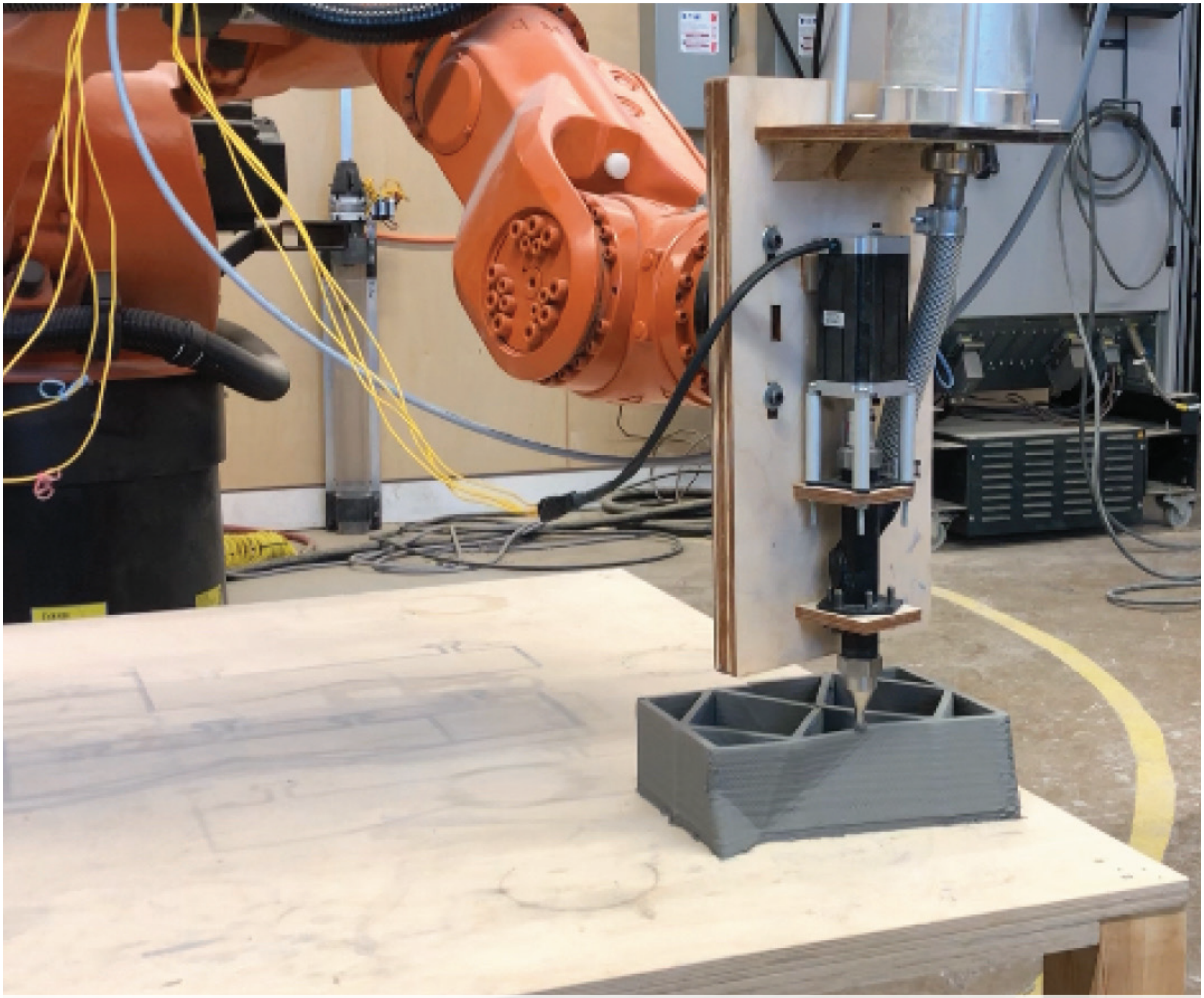


Figure 29. Photo shows the Kuka printing one of our modules. Photo by Authors

In hopes of creating a wall with a cohesive design that could be broken down into unique individual bricks, this design was inspired by the Voronoi diagram which makes a single plane into regions in a certain proximity to a series of points. After creating the plane, the regions were extruded to different depths to create faceted ledges and overhangs to potentially be used for planters or water collection. A pair of these bricks were prototyped with relative success using the robotic arm but their design needed revision. After printing we concluded that it would be better to create a cohesive, organic design for the overall wall instead of a faceted wall made up of geometric units that are split into different geometric units. The design was an interesting parametric exploration, however it did not speak to our intentions of taking advantage of natural processes like water collection and plant growth.

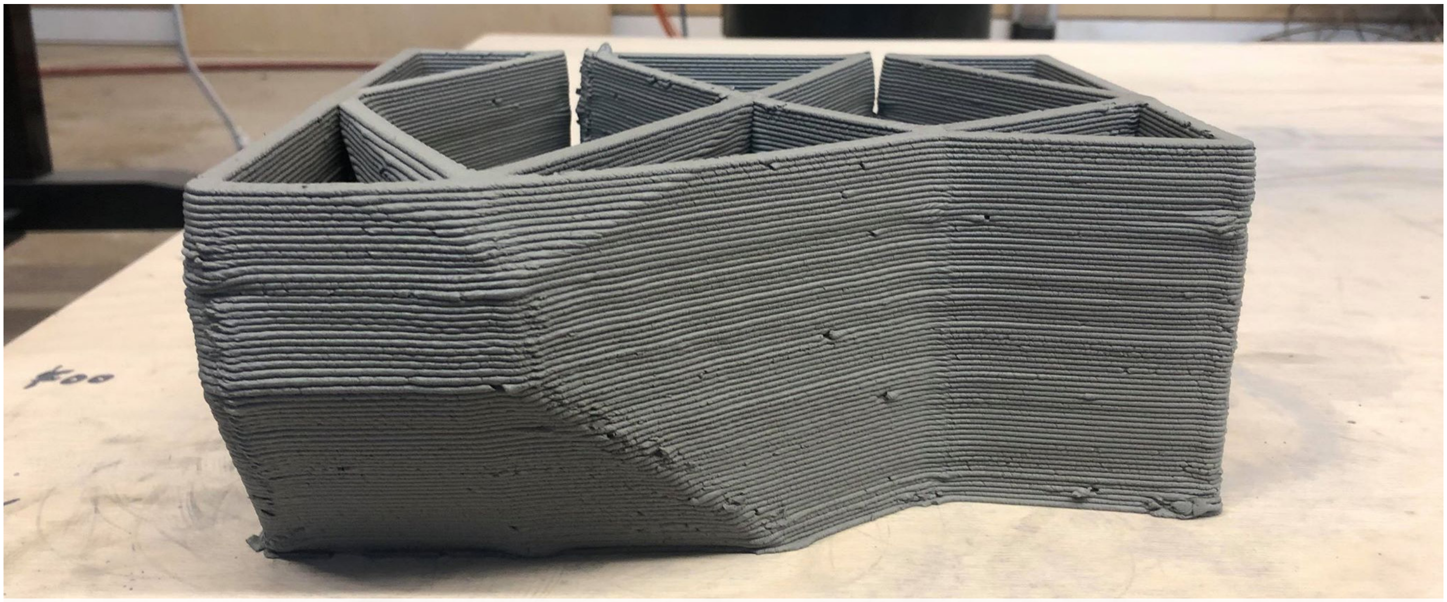


Figure 30. Photo shows one of our test modules. Photo by Authors

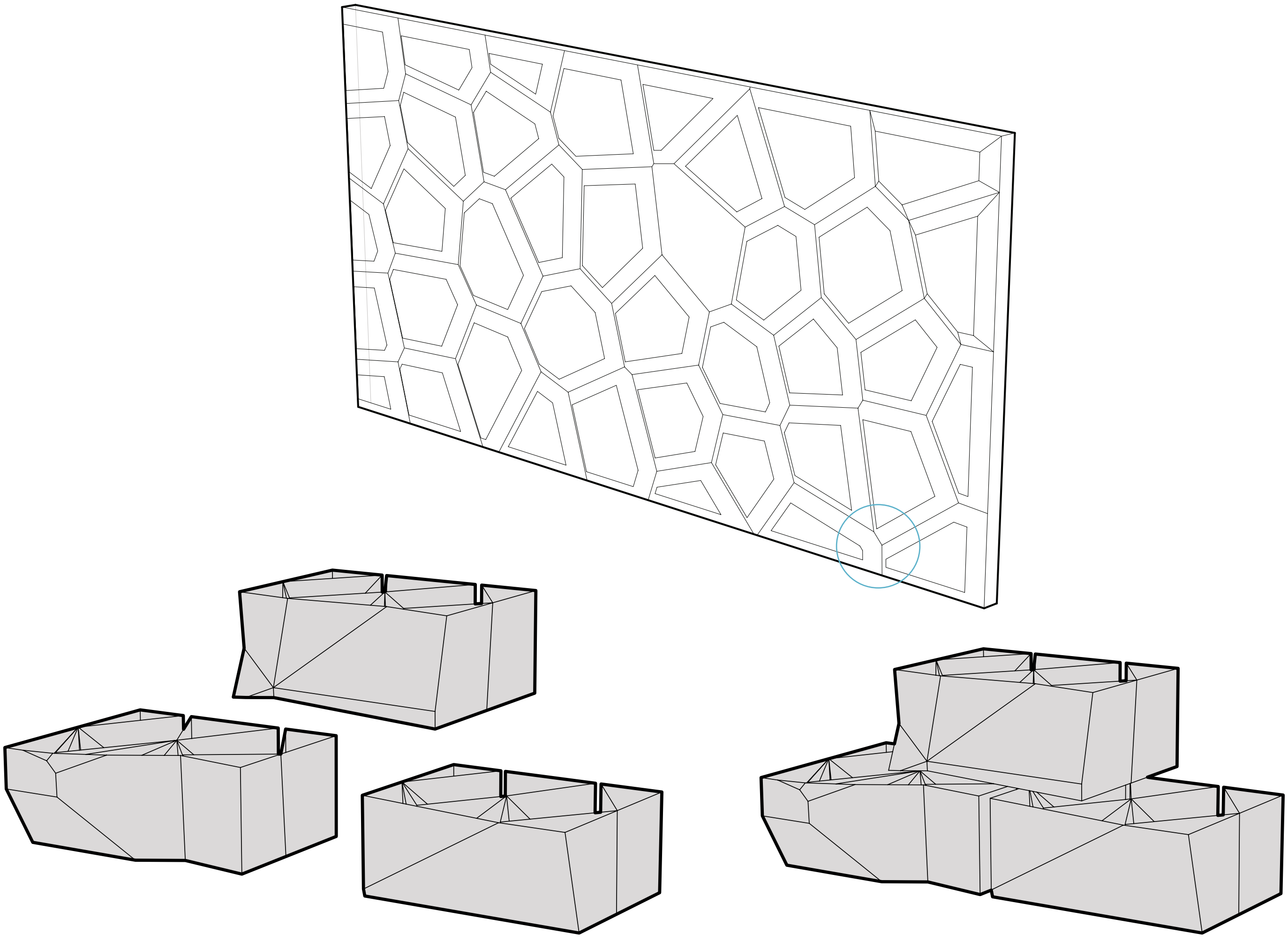


Figure 31. Shows the overall wall assembly as well as the 3 modules we attempted to print. Photo by Authors

Concept #4

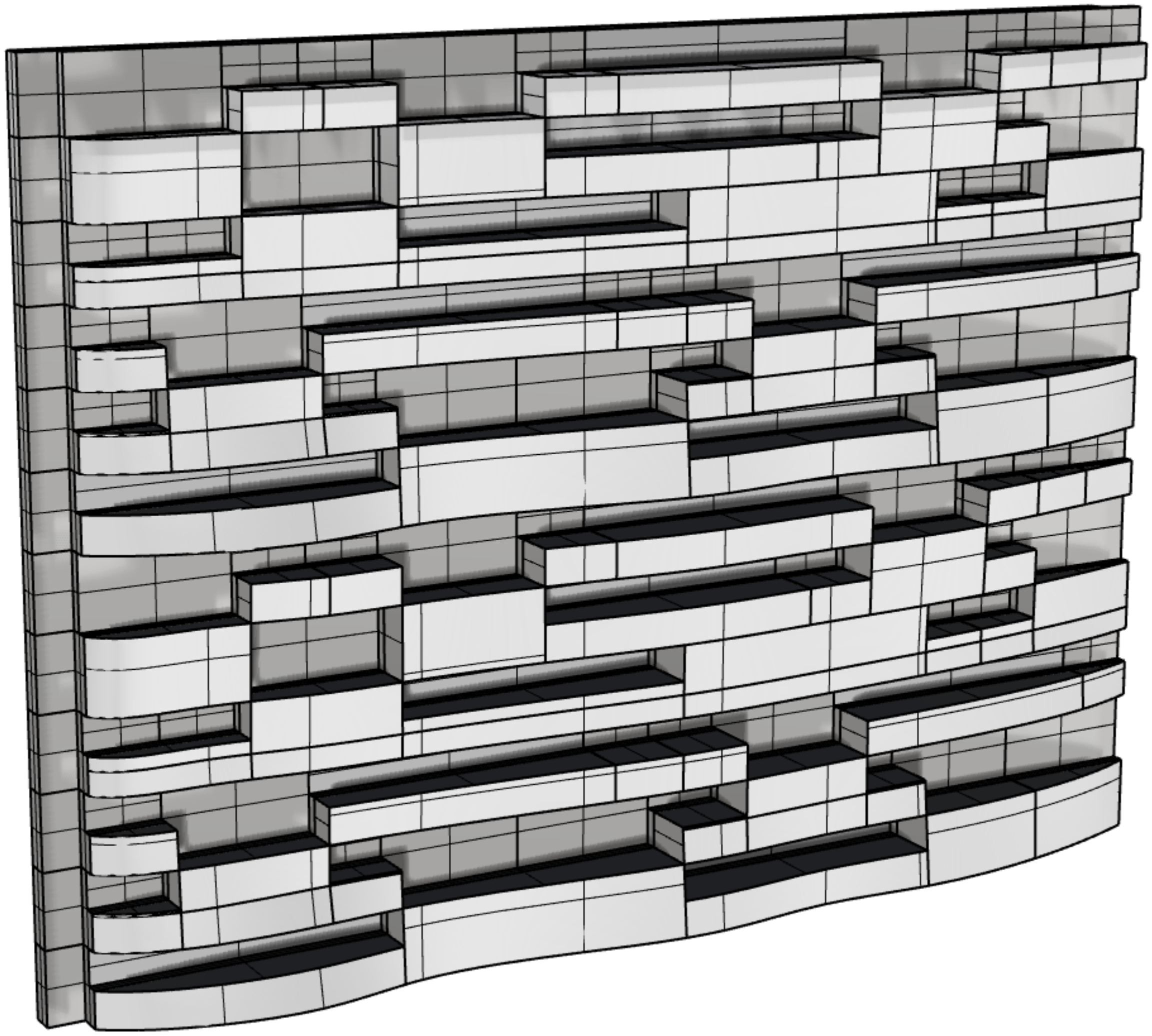


Figure 32. Shows one of the concepts that utilized the graph mapper. Photo by Authors

This iteration we began to establish some different possibilities for our structural chambers that make up the back end of our wall. We decided that we would have 4 layers: vegetation, water, air and insulation. Additionally, this variation we experimented with different sized modules that could interlock using a z connection and worked off of one standard unit. The units we decided on was based off of a 1x1 (6”x6”) making variations such as 1x2, 1x4 and 2x2. These modes then formed the base of the wall where a surface was applied to give a more curvilinear form. The idea with these modules was that the water could drain straight down between planters until it reached the base of the wall. However, this variation was quite rigid, and we felt it was not adequate to just let water fall into the planters and wanted to curate the movement of water into the planters in a more significant way.

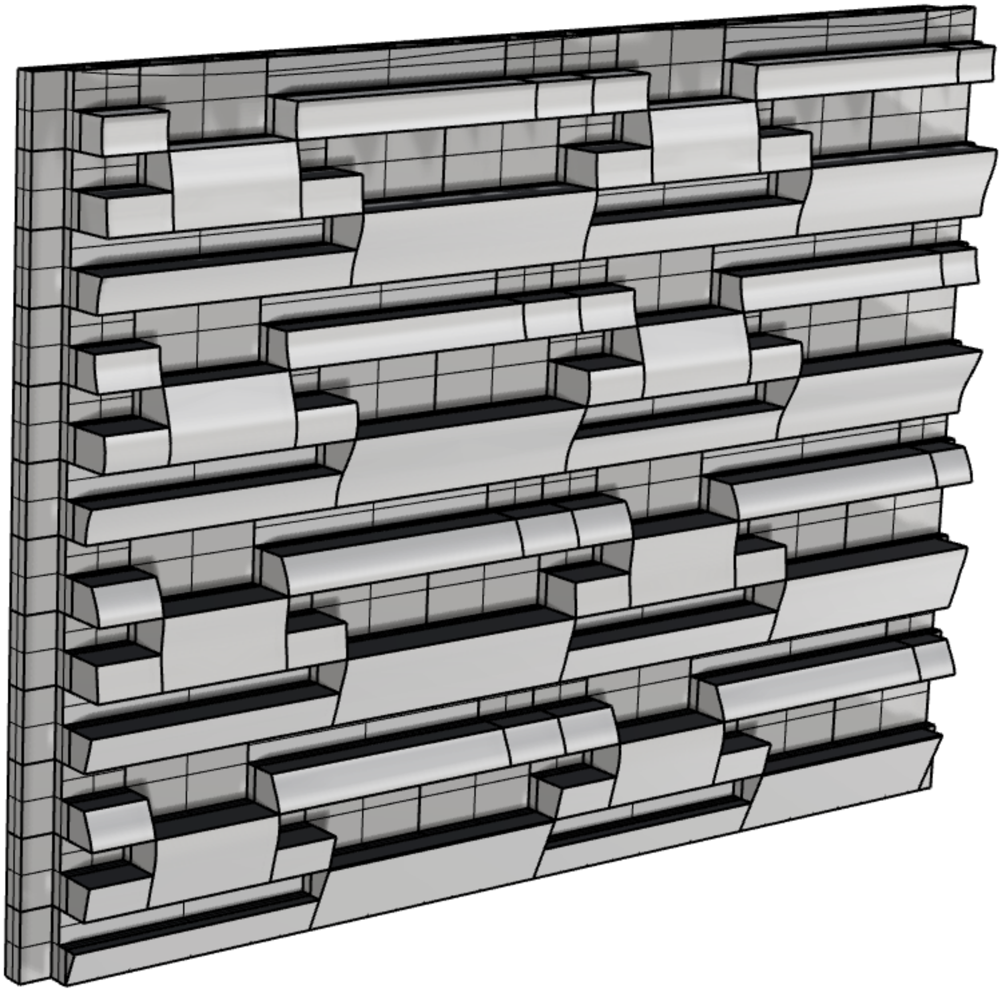


Figure 33. Shows a second iteration that utilized the graph mapper. Photo by Authors

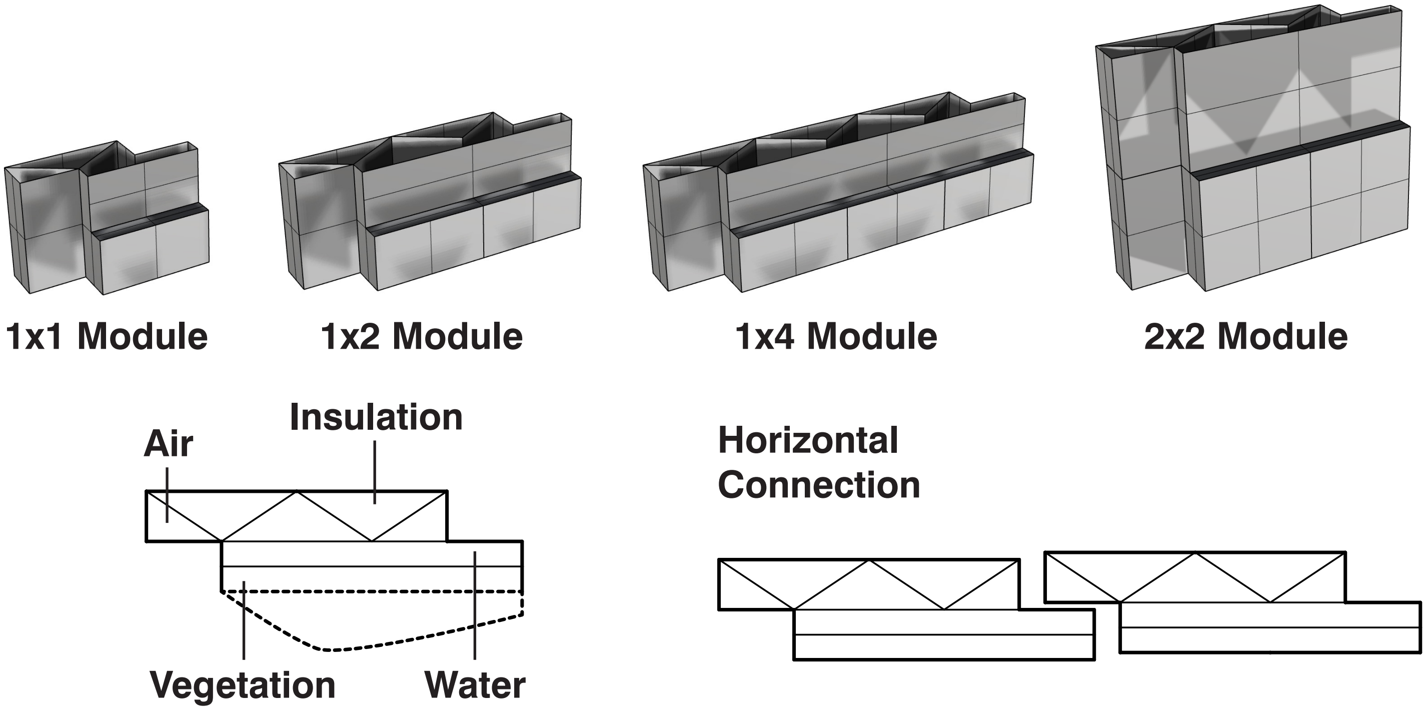


Figure 34. Different module variations, the various wall layers, and the z type connection. Photo by Authors

Test Print #3

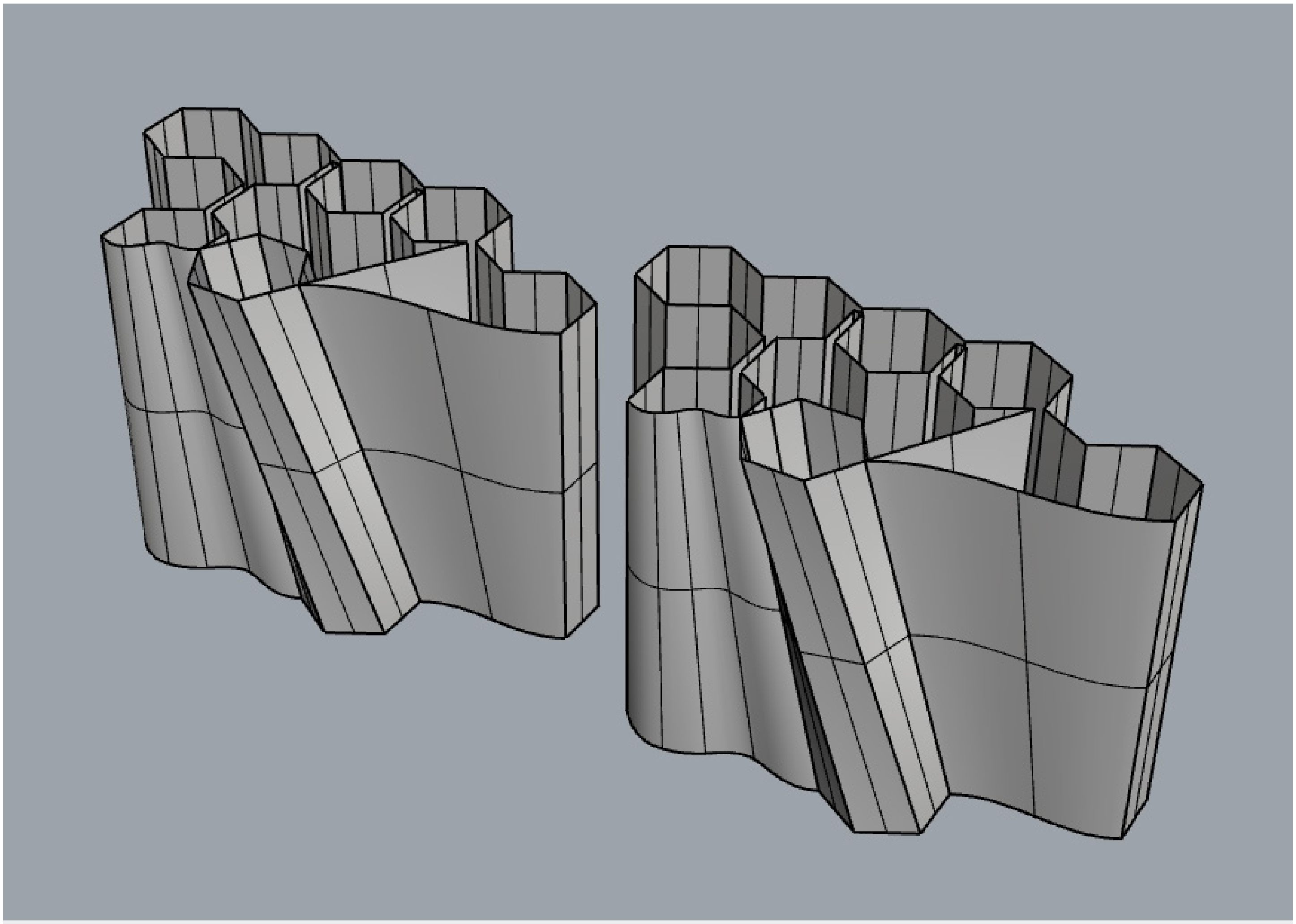


Figure 35. Test print modeled in rhino, showing back end intersecting with curvilinear form. Photo by Authors

Moving through design iterations, different concepts had been proposed as to how water could be directed or channeled throughout the facade system into defined planted areas. Two different methods of rainwater collection had been defined throughout our explorations. The first method was to explore how rain water could be collected along the exterior face of the wall assembly, utilizing organic forms of the facade to direct and manage the movement of water into identified planters. The other method was to develop water channels throughout the wall assembly that would funnel rainwater runoff collected from roof of the building and direct them to specified vegetated areas throughout the facade. The idea was to develop a wall assembly that could incorporate both of these systems cohesively, enriching one another to achieve an efficient water collection and irrigation system. This entailed exploring methods of incorporating water channels that would work in unison with the fluidity of the facade design. In which the water channels would have openings that would allow water collected from the roof to spew out onto the facade, from which form of the facade would direct the water from the roof and

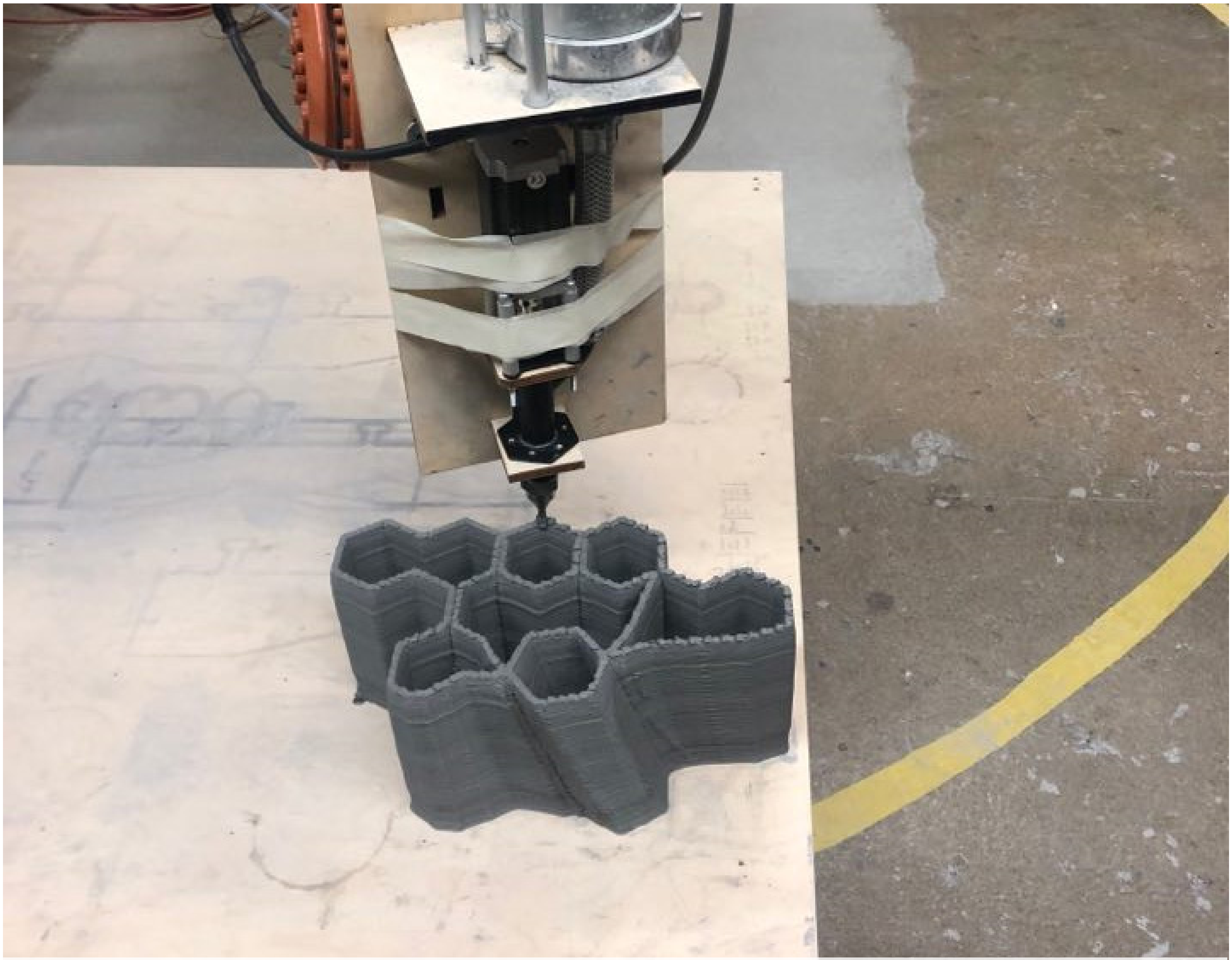


Figure 36. Test print #3 while printing. Photo by Authors

additional water collected on the surface of the facade into the planters. Additionally, the facade would incorporate areas where rainwater hitting the surface of the wall as well as water spewed out from the water channels could be collected and re-introduced back into the water channels and irrigation system of the wall.

This print was our first ceramic print that explored the concept of water channels being incorporated into the facade while exploring how the hexagonal reinforcing of each brick module forming the insulation, air and water layers could act as lateral interconnections between brick modules. In order to develop the module to be printable through the grasshopper script and Kuka PRC plugin, the design was to be broken into two printable passes, that of an internal layer/pass and an external layer/pass. This was due to the incorporation of a printable tube that was to be interconnected with the exterior facade, which meant that the tube was to be split in half and printed through the two passes of the internal and external layer.

Concept #5

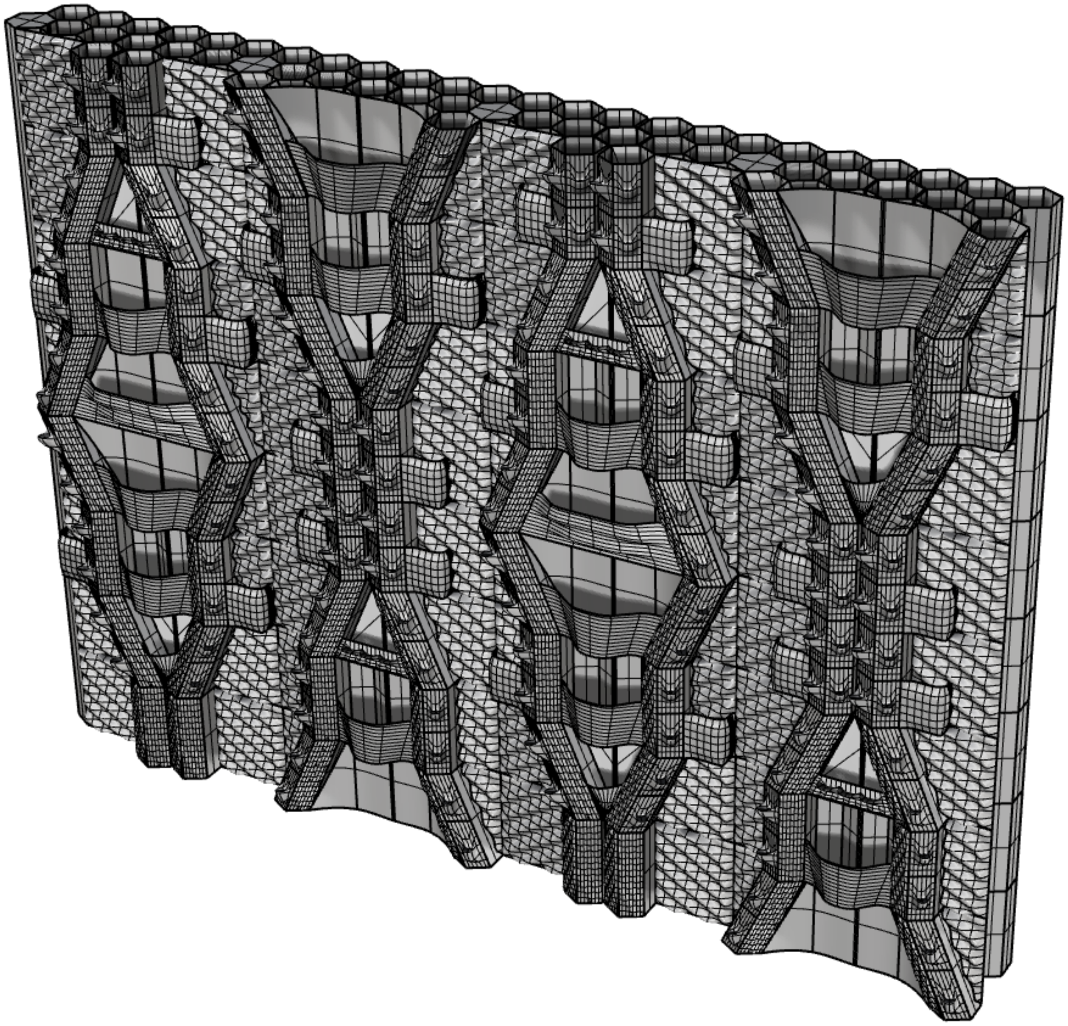


Figure 37. Wall concept that attempted to integrate planters and water channels. Photo by Authors

After experiencing problems integrating multiple functions within each brick, an idea was proposed to have different modules that could each serve its own function for vegetation, collecting water, or directing water. As a result, this design concept used a standard hexagon back end, and incorporated several different modules which could then be aggregated in different ways. Versus previous concepts that had designated collection basins to then transfer water into the tubes, this proposal added small collection leaflets onto each tube so the water could enter the tubes efficiently.

Although the leaflets were an interesting concept for collecting the water and establishing a more integrated water collection and vegetation system, there were clear issues due to the forms of the modules. The biggest issue was the flat condition of the planters and water collection basins could not be achieved using our existing grasshopper script. Additionally, the form of leaflets and the opening on them leading into the tubes would not be possible because there would be no proper support while 3D printing. As a result, although interesting this test wasn't feasible.

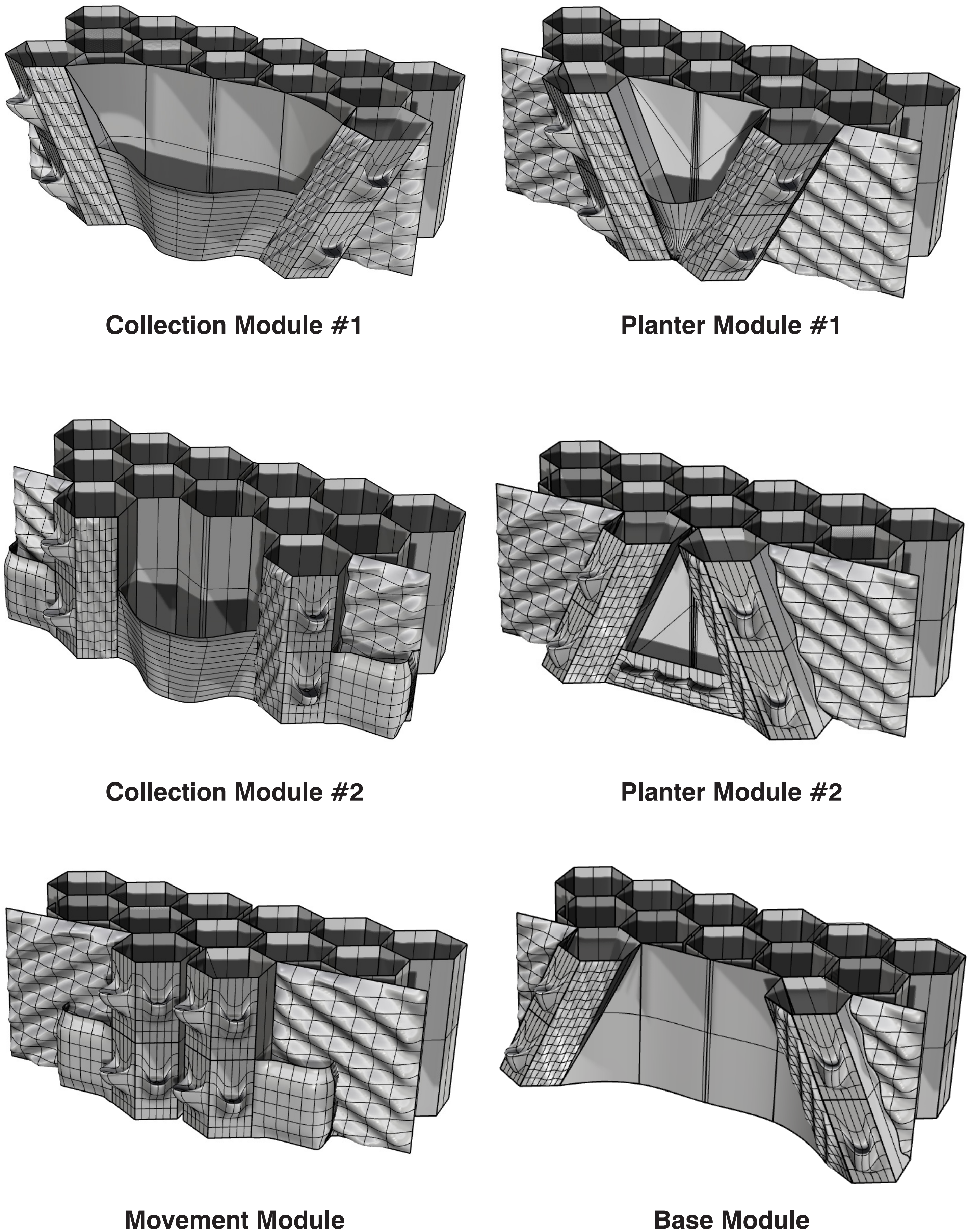


Figure 38. Various module variations which each serve a function. Photo by Authors

Concept #6

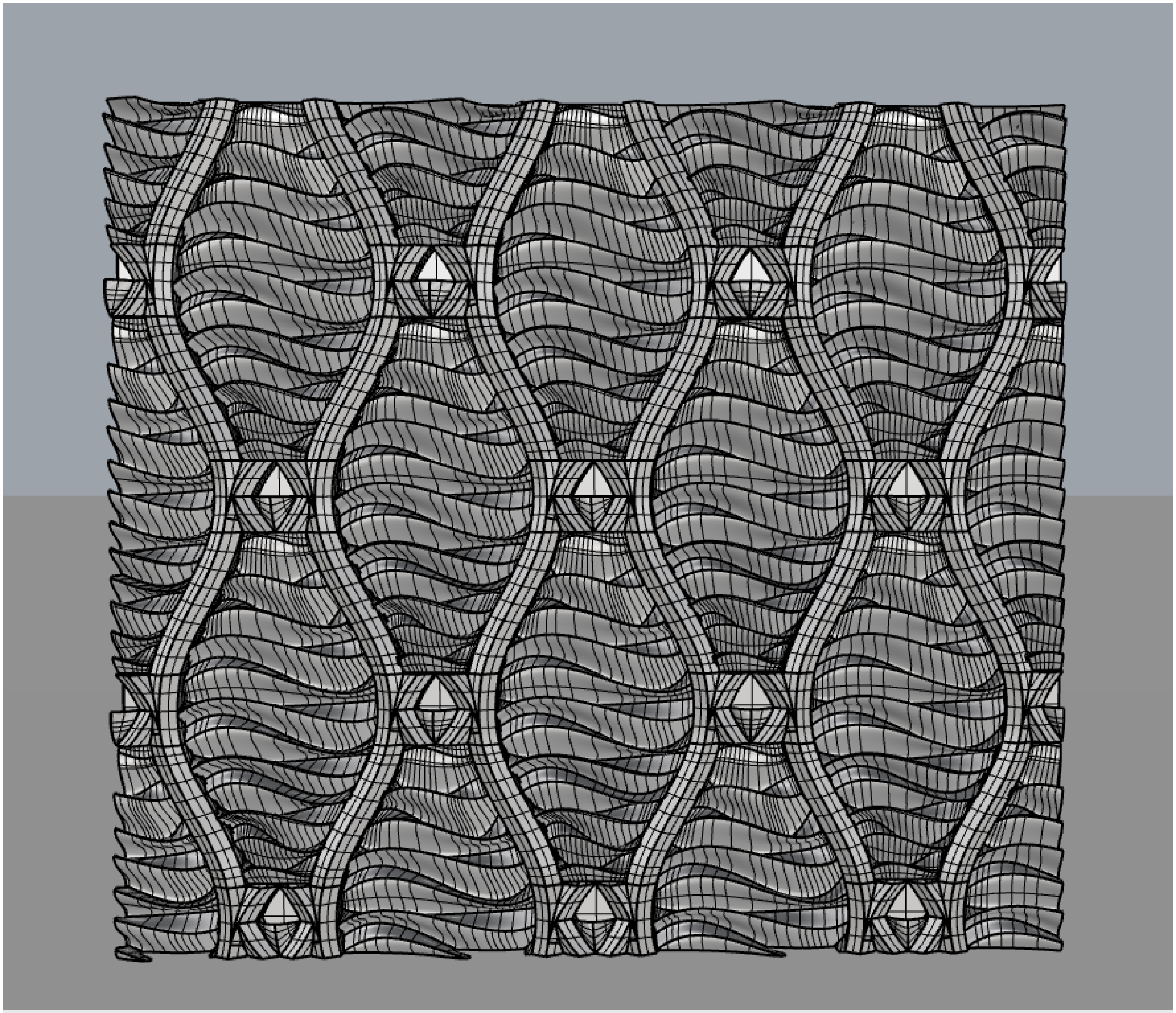


Figure 39. Concept #6 wall. Photo by Authors

Furthering the concept of how the water channels and the facade could work in a cohesive manner, this design explored the manner in which the design of the facade could perform similarly to that of leaf petals. In which the water collected on the facade would transition from petal to petal, evenly distributing water from each planter within each petal to the next petal and planter below. Additionally, water channels were positioned to be able to distribute water onto the front of the facade through spout openings in the middle of every section. While providing a water collection system above the water spout condition where the rainwater directed throughout the facade could be reintroduced into the water collection system and redistributed throughout the rest of the facade below. This concept proved to be challenging in terms of print ability, therefore the concept wasn't explored in more depth.

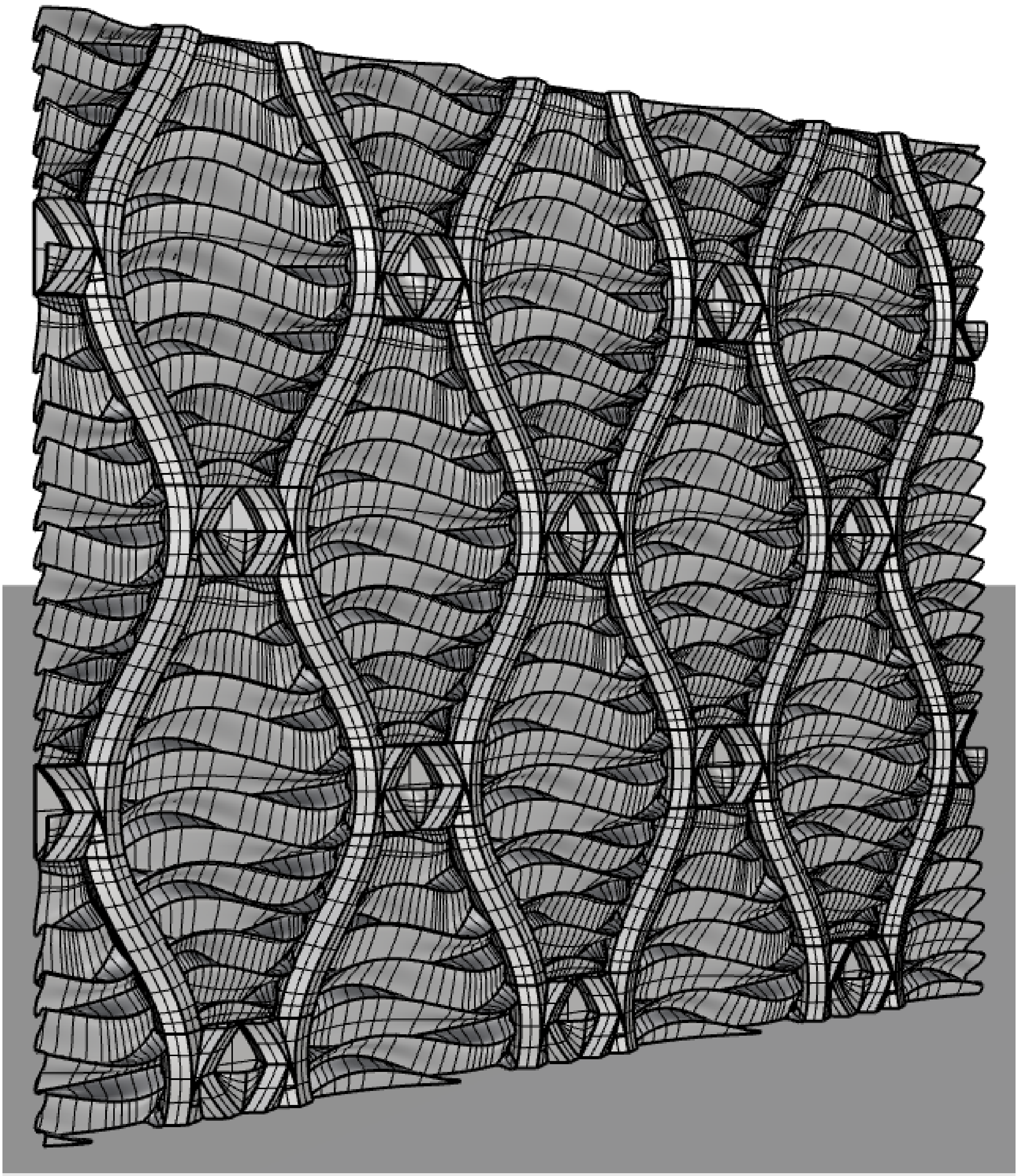


Figure 40. Planters were intended to spill over into one another. Photo by Authors

Concept #7

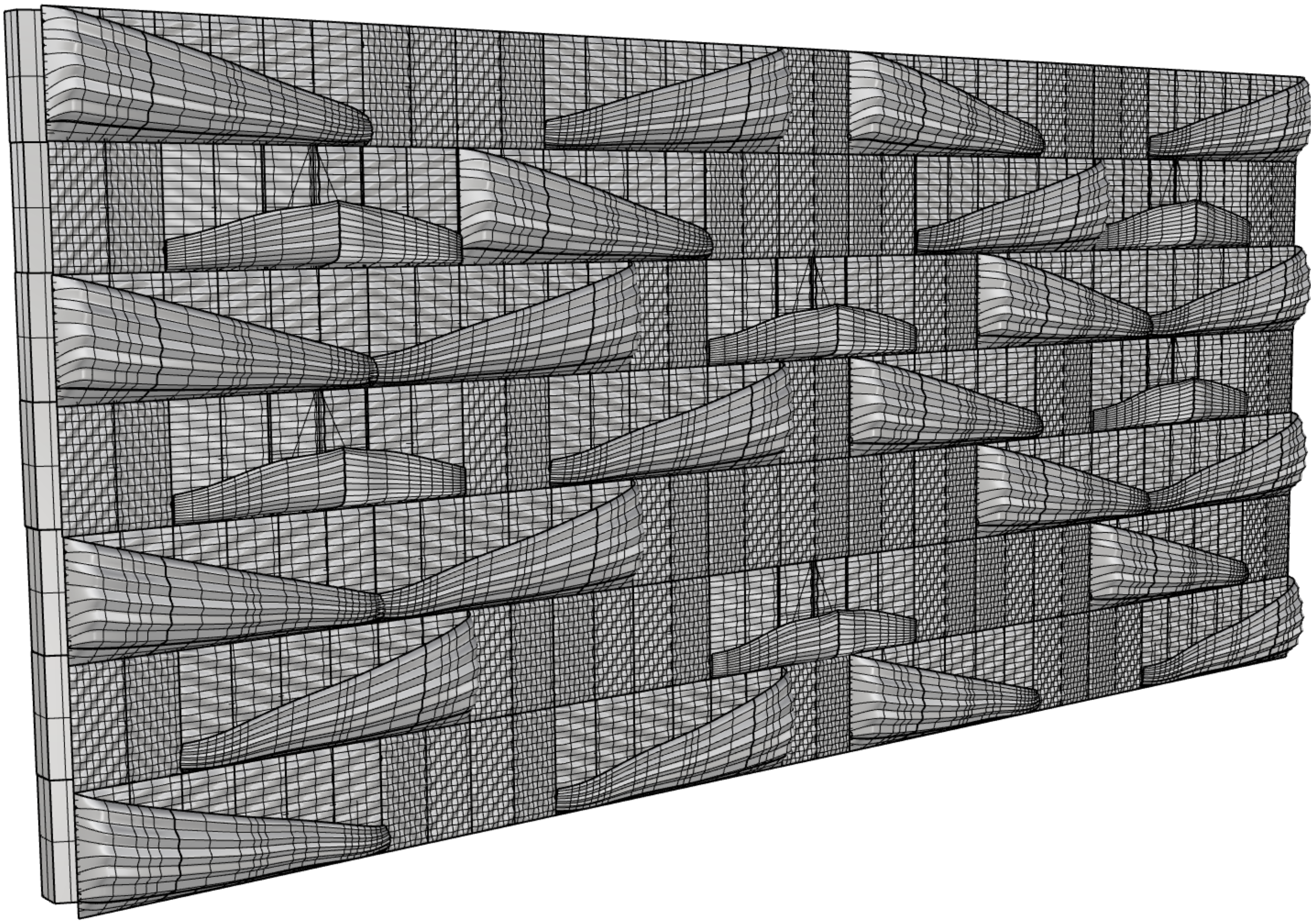


Figure 41. Wall was based on simplifying planters and eliminating channels. Photo by Authors

This concept was one of our first attempts at a wall assembly that did not use tubes to transport water. The idea was that the majority of the movement would occur once the planters were filled with water, causing water to spillover into other planters. This is why the planter modules are more narrow at one end because once the water filled to this point it would spill over. Additionally, smaller rippled modules were introduced as a less direct way of moving the water towards the planters. The idea of the finer ripples was something we liked and wanted to move forward with in our future iterations.

Finally, this system also began to look at the hexagonal back end and how it could begin to aggregate, using a standard back end to the facade. We decided on a key connection for this version because it eliminated the tolerance difference we saw when staggering modules on top of eachother ensuring that the backend hexagons lined up so we could achieve our lego connection vertically. Although this test provided some interesting things to move forward with the overall design was too rigid and not experimental enough for our liking.

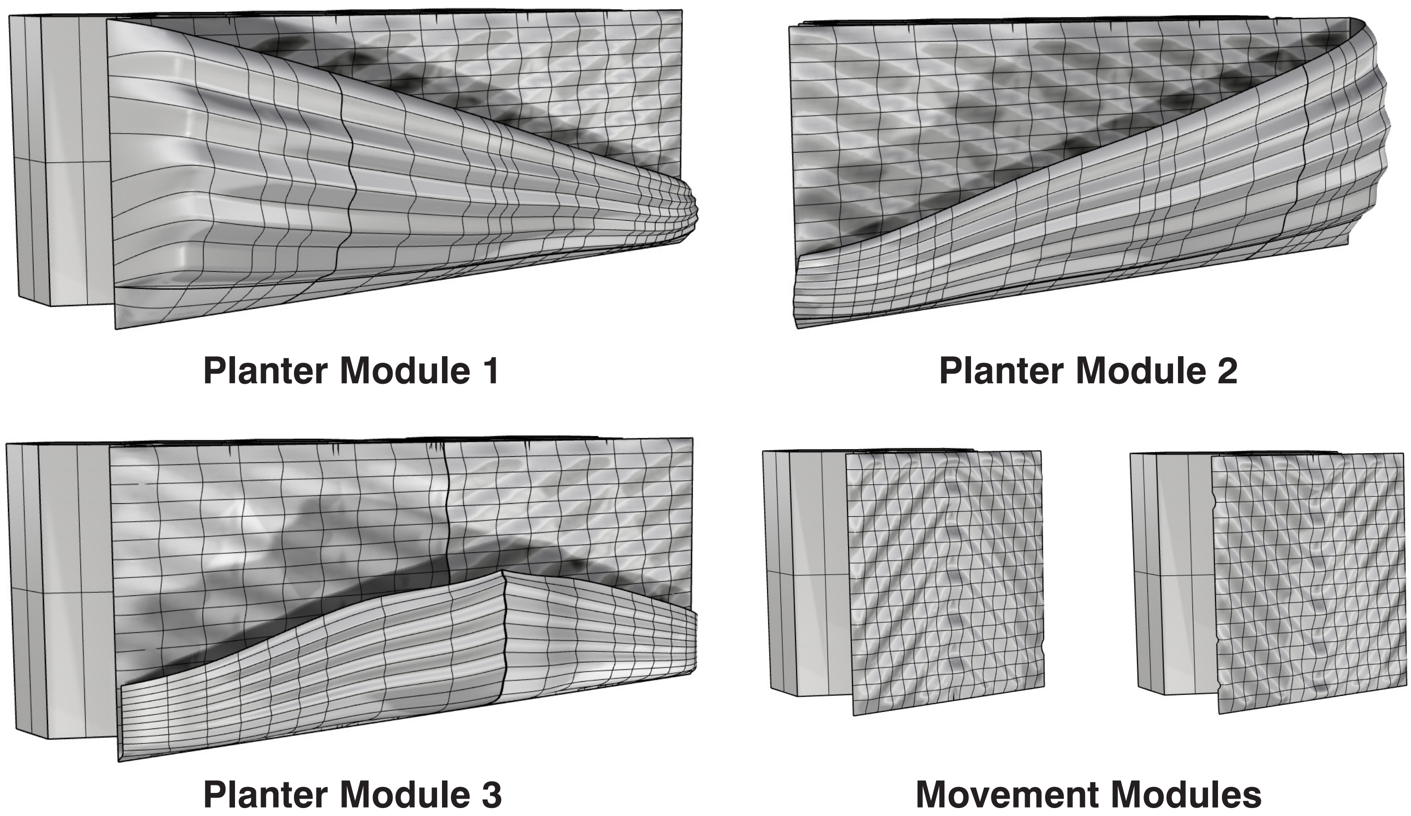


Figure 42. Various simplified modules. Photo by Authors

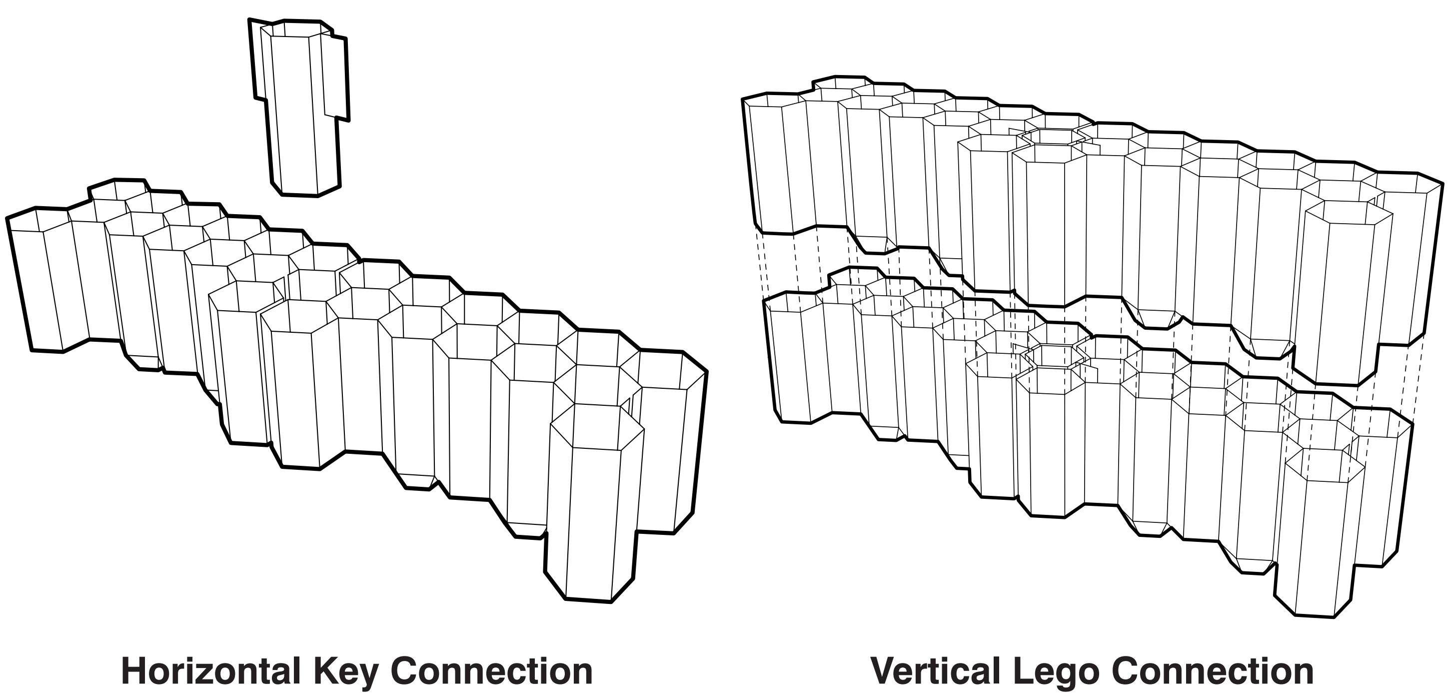
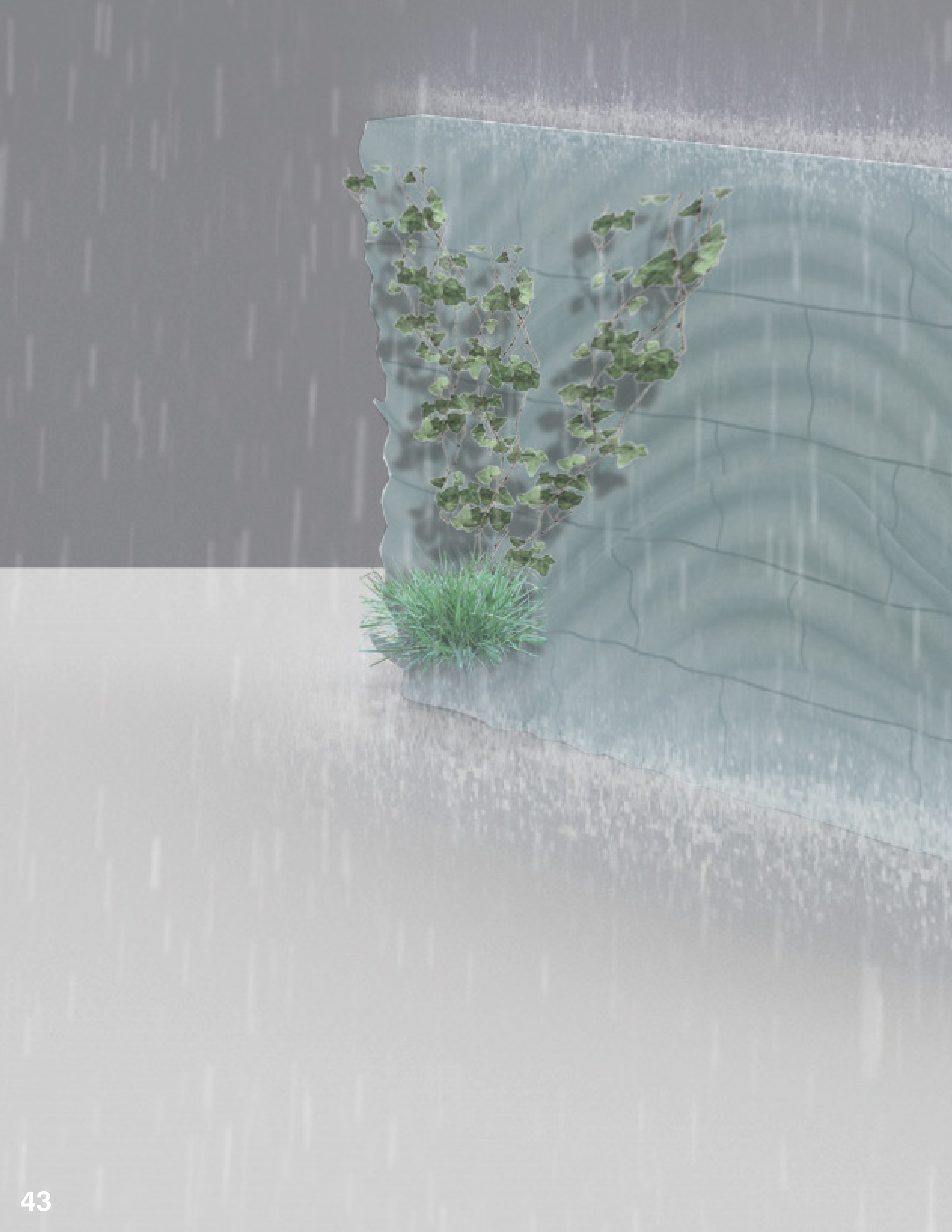


Figure 43. Strategy for connecting modules vertical and horizontally. Photo by Authors



Final Design

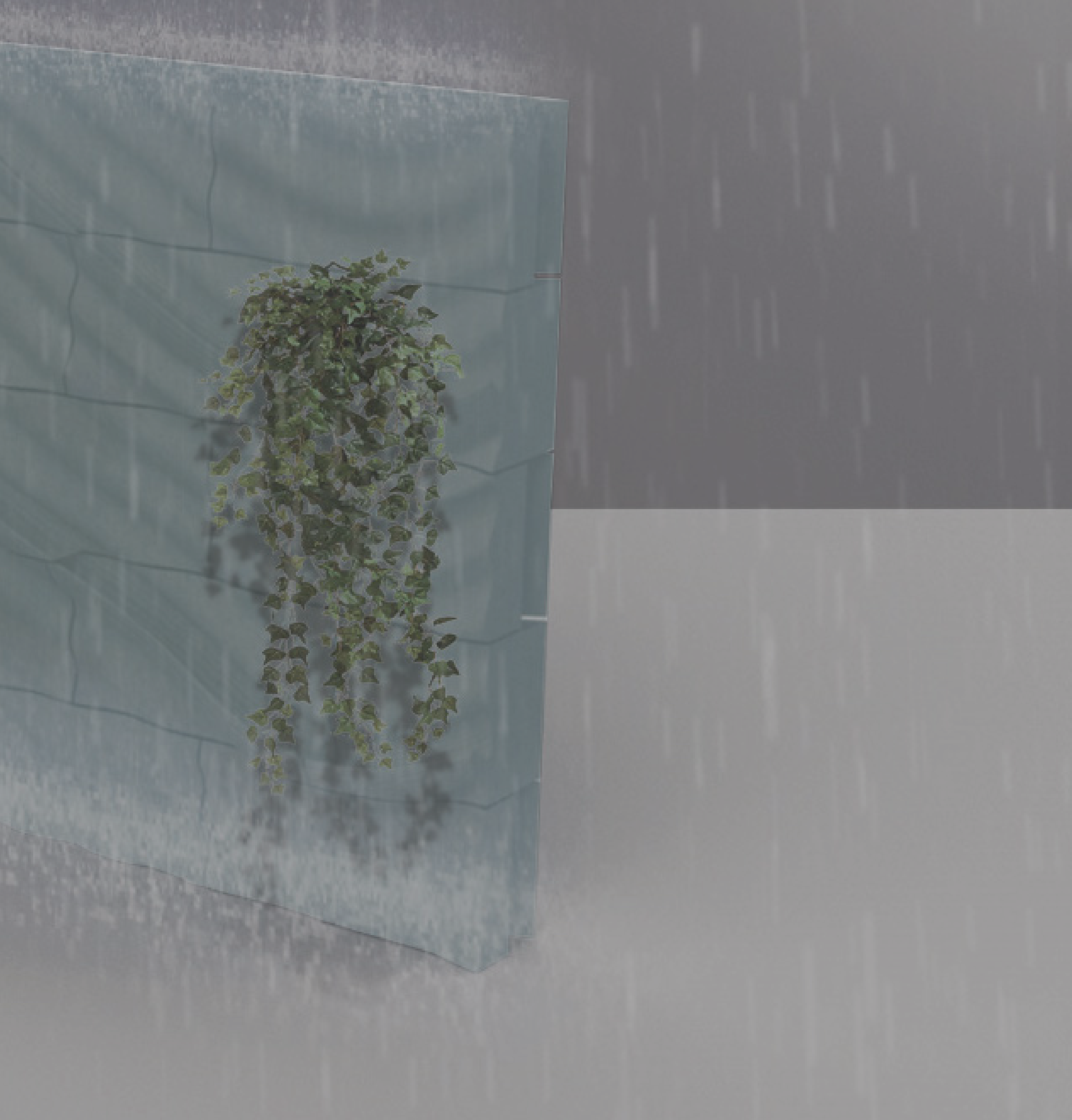


Figure 44. Final design. Photo by Authors

Final Design

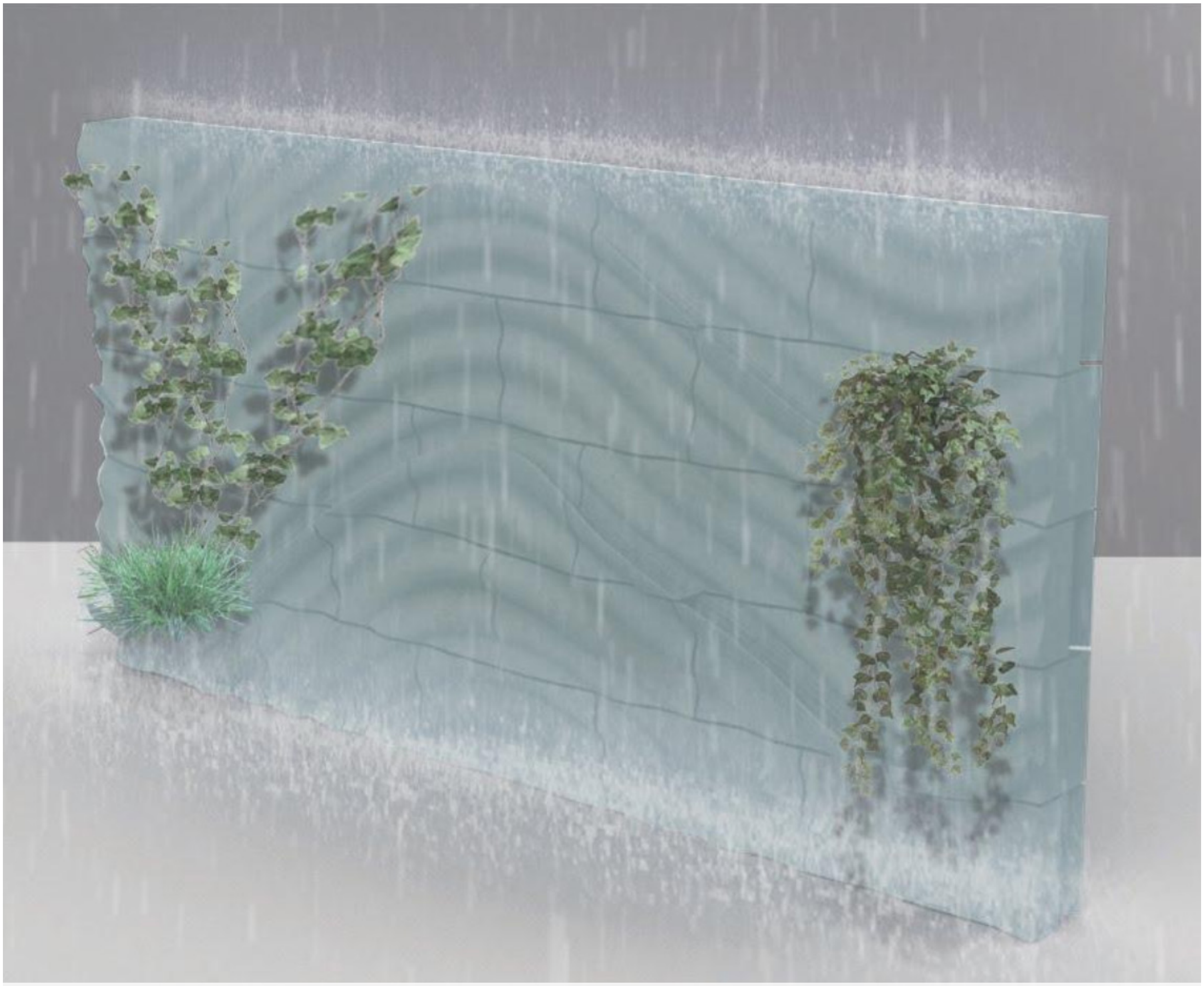


Figure 45. Final design incorporates movement of water and planters. Photo by Authors

Our final design is an integration of our two driving concepts; water collection and integrated greenery. This system is designed as a stand-alone piece or added to a structural system as a façade element. Its rippled, undulating surface creates moments of more dramatic water dissipation and collection. Inspired by the ripples on the surface of water as it rains, the walls rhythmic curves are projected onto an uneven flowing surface which gave the opportunity to exaggerate certain curves away from the wall and dictate basins and ledges for water movement as well as three integrated planters in areas where the most water would be passing or collecting. The internal structure is a refined hexagonal grid designed to slot into one another laterally and vertically. Moving forward the design of a corner and roof condition using this system would make its application more successful.

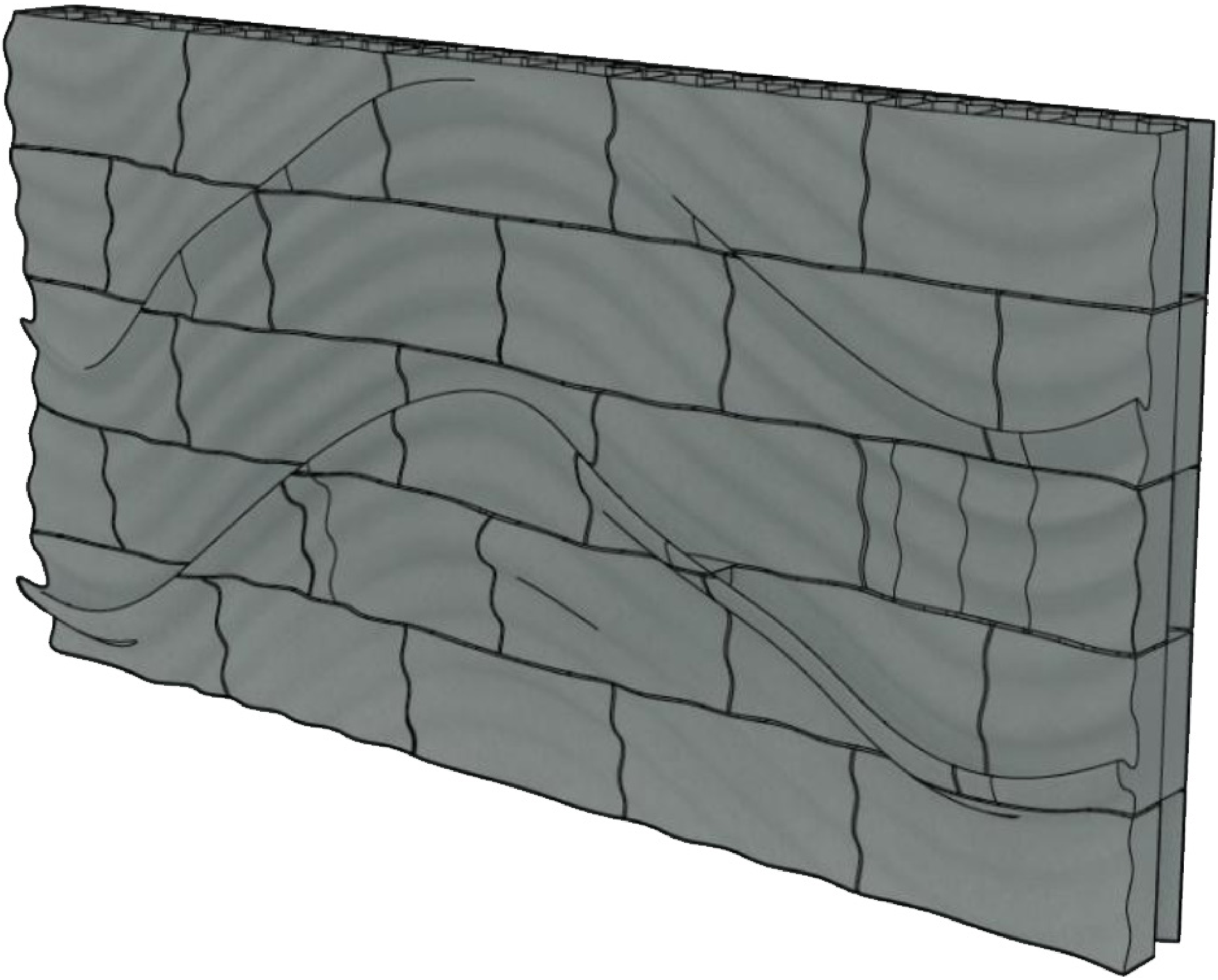
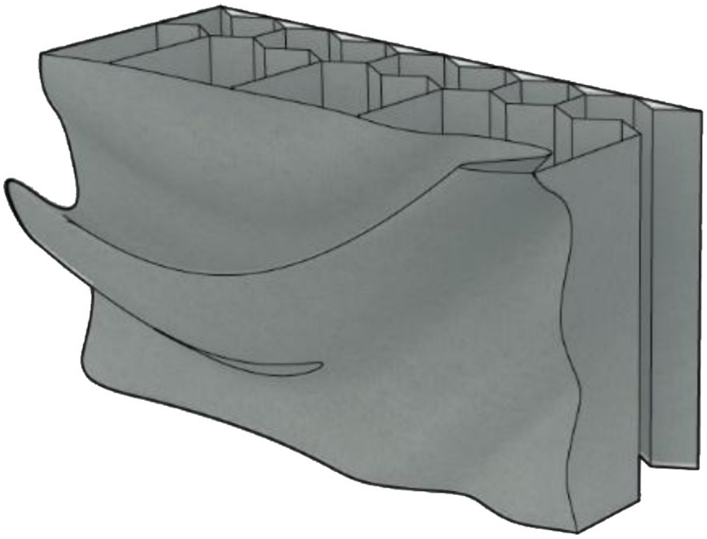


Figure 46. Final design line drawing. Photo by Authors



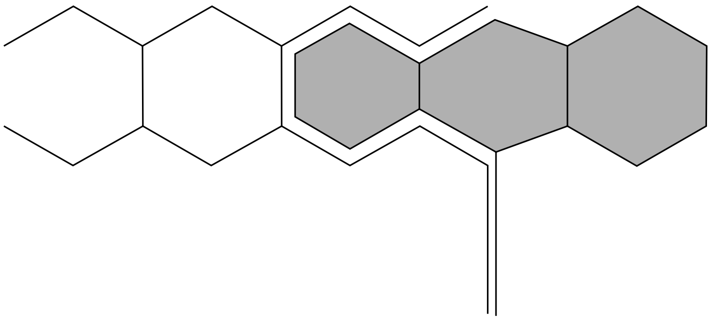


Figure 47. Brick Module and connection. Photo by Authors

Parametric Design: Printing Script

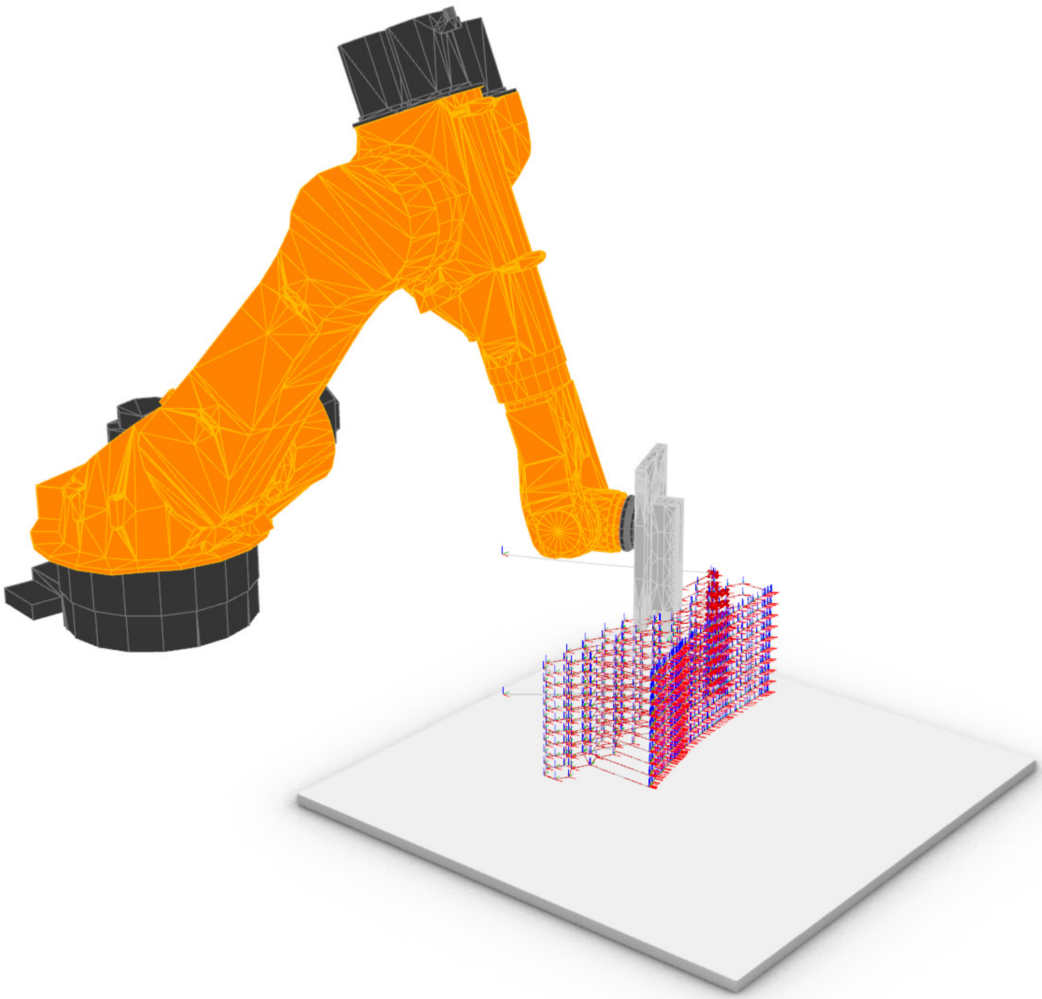


Figure 48. Shows the Grasshopper script used to print the back end of our module. Photo by Authors

Through the duration of the course, the printing script by our professor was altered significantly. Initially, the robot was only able to print clay if it was a continuous print. This meant that we could only print a single unit of closed geometry. With the capability of controlling digital outputs on the kuka robot, we were able to begin testing clay prints with stop and start functionality. This was very exciting because it allowed us to begin printing modules that incorporate multiple closed geometries. This way we were able to accomplish more complex brick modules which separated the front geometry from the connection portion of the back end, like in our final design.

Although, these geometries did need to be separated from one another on the printing bed. Further modification to the grasshopper definition was done in order to print closed geometry within one another. This was a crucial piece of the puzzle in order to create the water containment units that we were striving for within our final module. The use of a cup like condition was essentially impossible to achieve as a single organically modeled face, and the printing process had obvious limitations in that regard. In creating a pooling geometry that was separated from the face, the unit is able to be printed while performing an essential function.

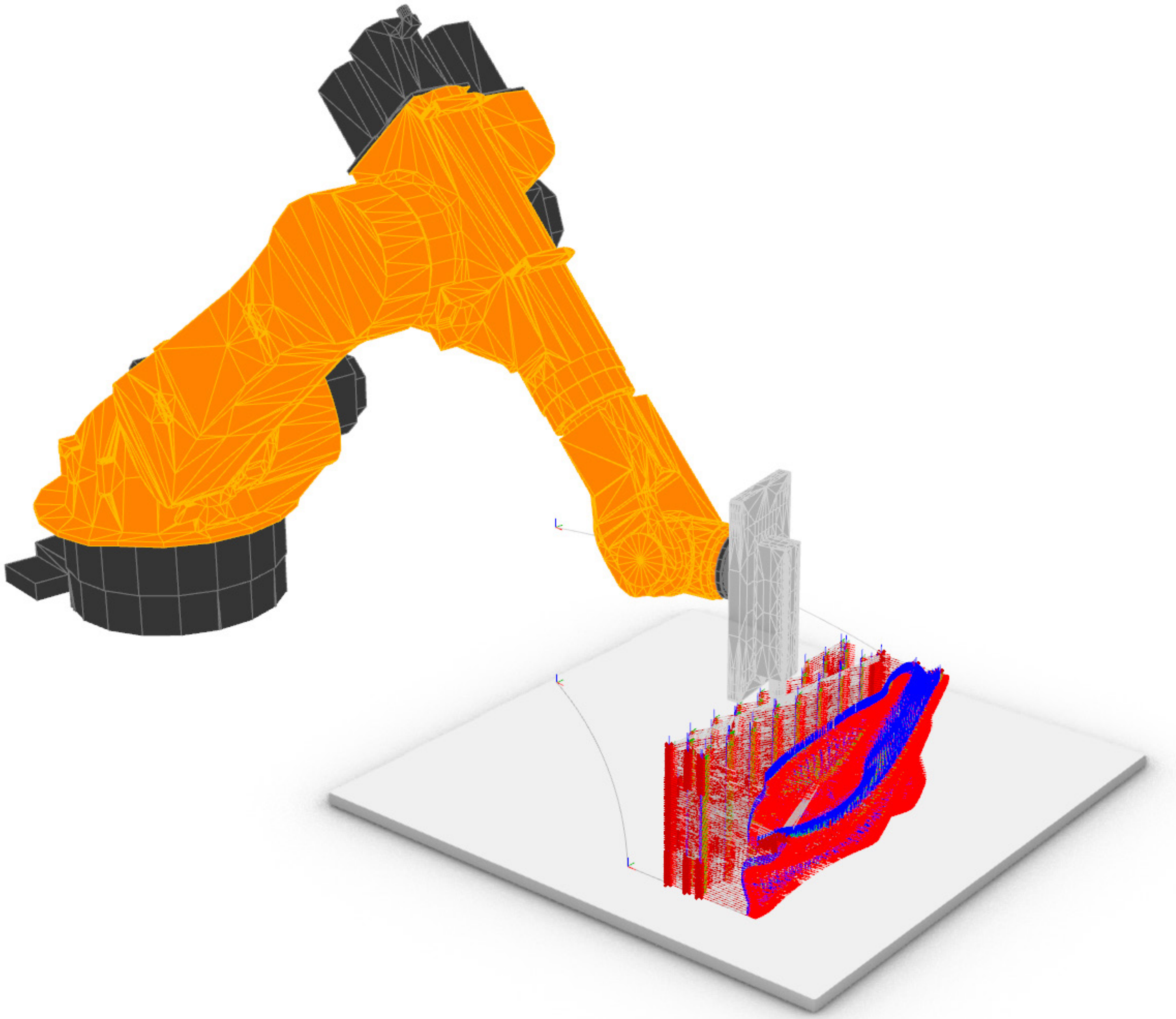


Figure 49. Shows the script used for printing the planters for our final module. Photo by Authors

Conclusion

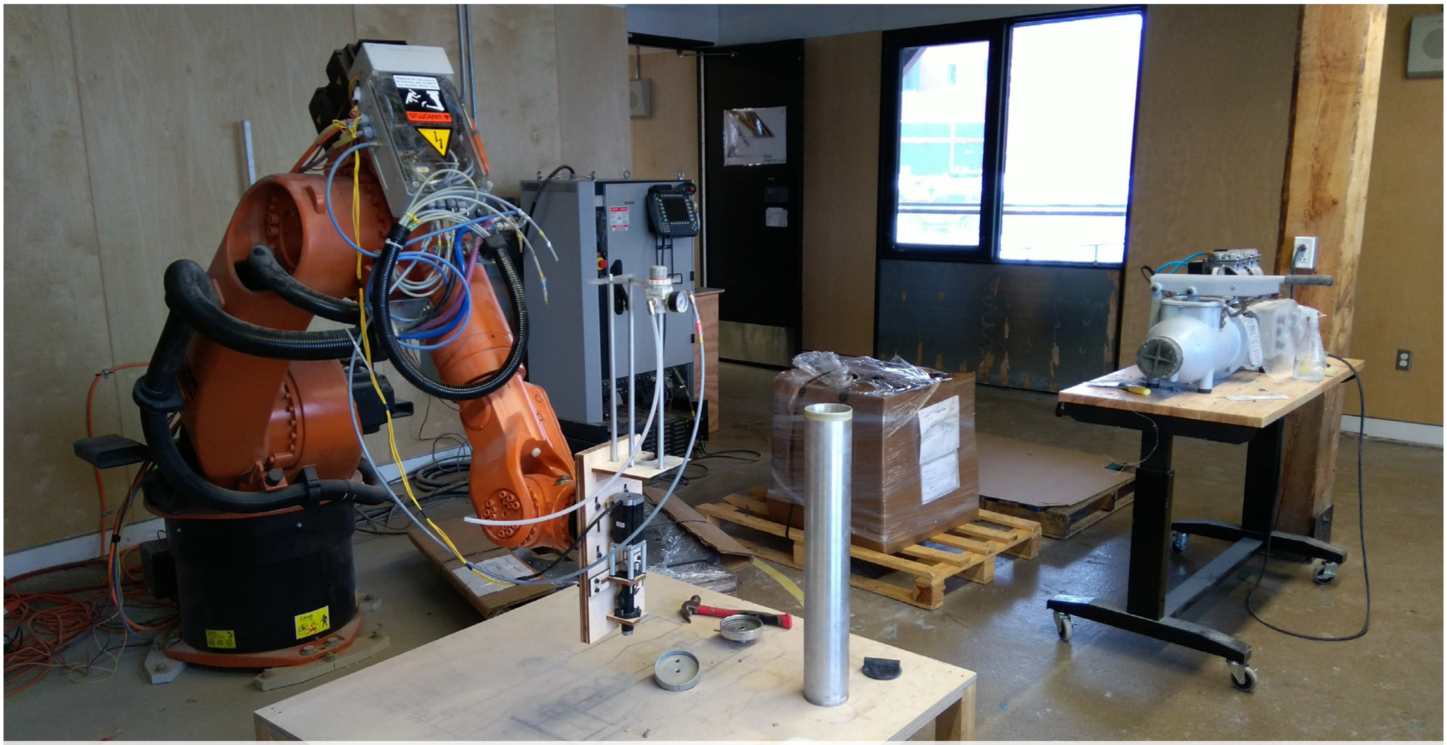


Figure 50. Kuka Robot. Photo by Authors

In conclusion, our experimentations led to a greater understanding of the limitations and capabilities of 3D printing with the Kuka Robot. This was achieved by understanding the inherent properties of clay as a building system, through experimentation and testing. Our initial design concept of generating a performative facade system through the employment of ceramics as a system that worked towards mitigating and collecting rainwater runoff through the introduction of greenery successfully informed our progression to our final design. Although the final design achieved our initial goals and conceptual intentions, more explorations in regards to the printing of modules could be done in order to better understand the physical limitations of printing the cup planter conditions within each module. Additionally, for the overall theoretical success of a performative wall assembly to have been achieved, full scale wall assemblies would need to be printed in order to test out how water interacted with the undulations and planter conditions. Unfortunately, due to circumstances out of our control this was not able to be completed, but moving forward it would be integral to finalize our design. This would allow us to gather a stronger understanding of how water would move throughout our facade and help us determine the successfulness of the planters themselves in relation to water collection and mitigation. With the time constraints that was given with the project and the constraints that surrounded the adequate functionality and usability of the robotic fabrication lab, the project relatively successfully explored preliminary architectural interventions as to how ceramics can be utilized as a building system to create a sustainable, passive and efficient facade system.

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