TerrAqua

RESTORING MARINE BIODIVERSITY WITH 3D PRINTED CLAY REEFS

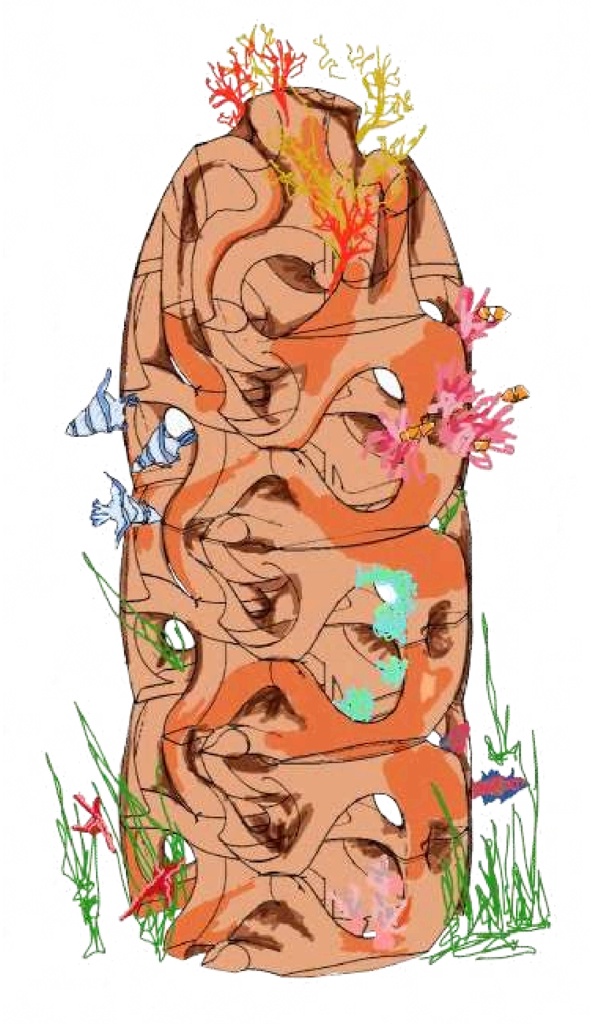
Author: Holly Adams

Local Mentors: Petra Garajová & Ana Correa
Global Mentors: Cecilia Raspanti & Oscar Tomico

Institute for advanced architecture of Catalonia

TerrAqua

RESTORING MARINE BIODIVERSITY WITH 3D PRINTED CLAY REEFS



Author: Holly Adams

Local Mentors: Petra Garajová & Ana Correa
Global Mentors: Cecilia Raspanti & Oscar Tomico

Fabricademy 2024/25

Fab Lab Barcelona - Insitute for Advanced Architecture of Catalonia

Barcelona, Spain
March 2025

Modular Assembly

INDEX

ABSTRACT

Key Words: Bioremediation | 3D BioPrinting | Regenerative | BioDesign | Conservation | Parametric Architecture | Organic Design

Coral reefs are the most vulnerable ecosystem to climate change, projected to have severly degraded by 90% worldwide by 2050. There is an urgency to develop advanced restoration techniques that can help repopulate and enhance biodiversity in these environments. Current reef restoration methods that utilise 3D printing seem to lack a design that promotes both marine and coral biodiversity. This design project aims to address this through the implementation of a modular 3D printed clay structure that is based off of a triply periodic minimal surface - in this case the gyroid. In collaboration with RRREEFS this structure will be tested in Pujada Bay, Philippines at their existing reef restoration site. Material fabrication included exploring an oyster shell and clay composite, however this was not successful and it was decided to continue with just terracotta clay. The final geometry was crafted using Houdini, Rhino 3D and Blender and printed with an ABB Robotic Arm Printer at 50% scale.

PREFACE

With a future goal of working at the intersection of Biodesign and conservation, I wanted to explore a research and design project that expanded my network of professionals working in conservation and preservation of the natural environment. As a result, I have been able to connect with a range of marine organisations all of whom are at the forefront of storytelling, exploration, or advanced fabrication. It has been interesting to see that most of the people who are working to protect the environment have actually never heard of Biodesign or the potential it has to create a more sustainable world!

With the skills I had learnt from Fabricademy and the resources available at IAAC, I believed it to be a great opportunity to develop 3D printing skills with the bio-paste printers and robots. This project has allowed me to find my niche within Biodesign and I am excited to continue advocating for this field within the conservation industry.

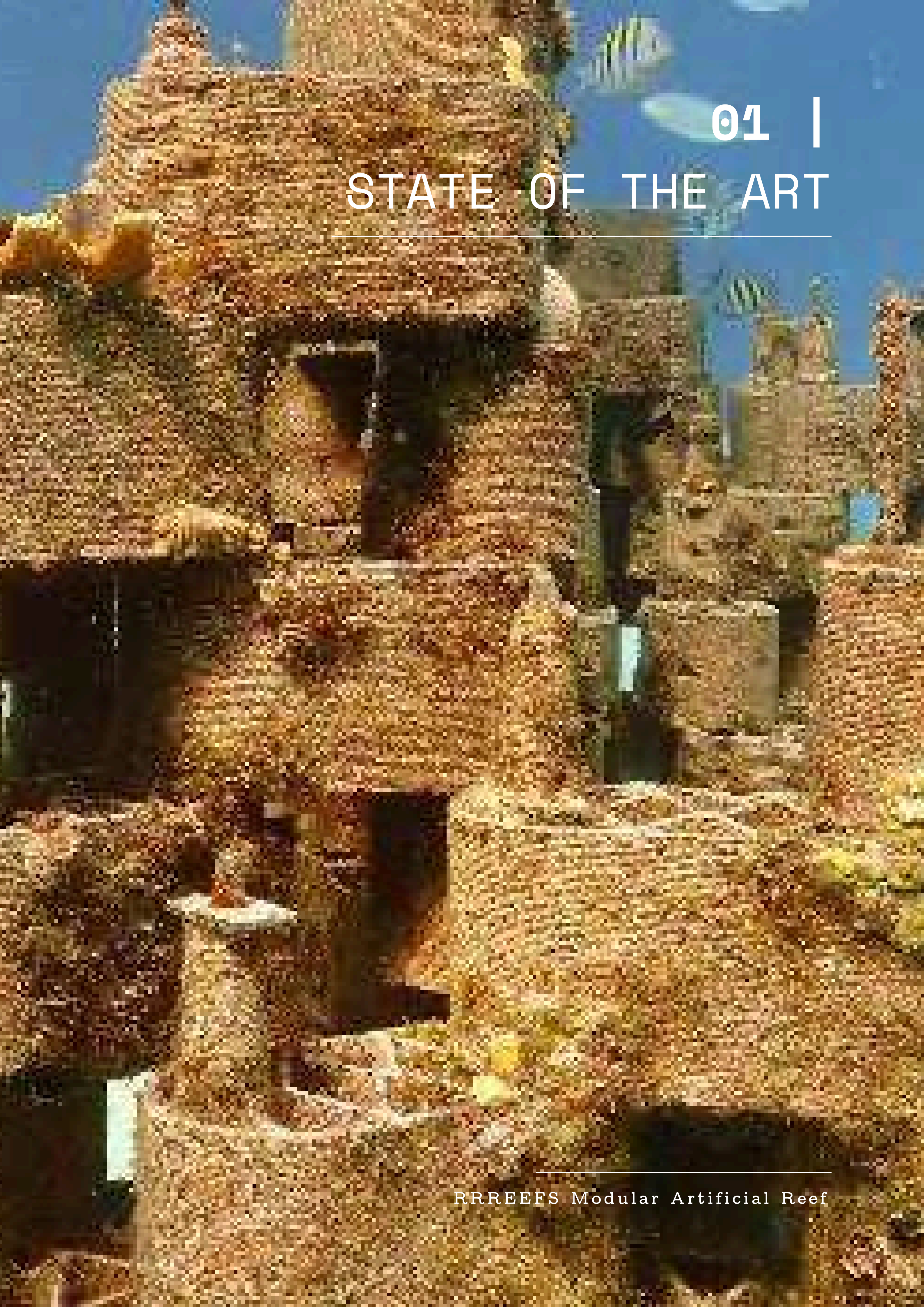
ACKNOWLEDGEMENTS

Firstly, I would like to deeply thank my two Fabricademy instructors, Petra Garajova and Ana Correa, who provided constant support, insight and guidance throughout my time in Barcelona. Along with all the FabLab Barcelona team, Danny Mateos, Adai Surinac and Josep Marti, who were always so patient and wise with any problem that occurred - no matter how many things I broke! I looked up to you all immensely for the amount of knowledge you had about everything and I am incredibly grateful for the time I spent at IAAC. Fabricademy was exactly what I needed to set me on the path I wanted to take and I feel so enriched even after 6 months.

Finally I would like to extend my thanks to the wider FabLab network especially Anastasia Pistofidou and my global mentors, Cecilia Raspanti and Oscar Tomico who allowed me to think rationally and conceptually through my project, refining it in ways I had not thought before.

01 |

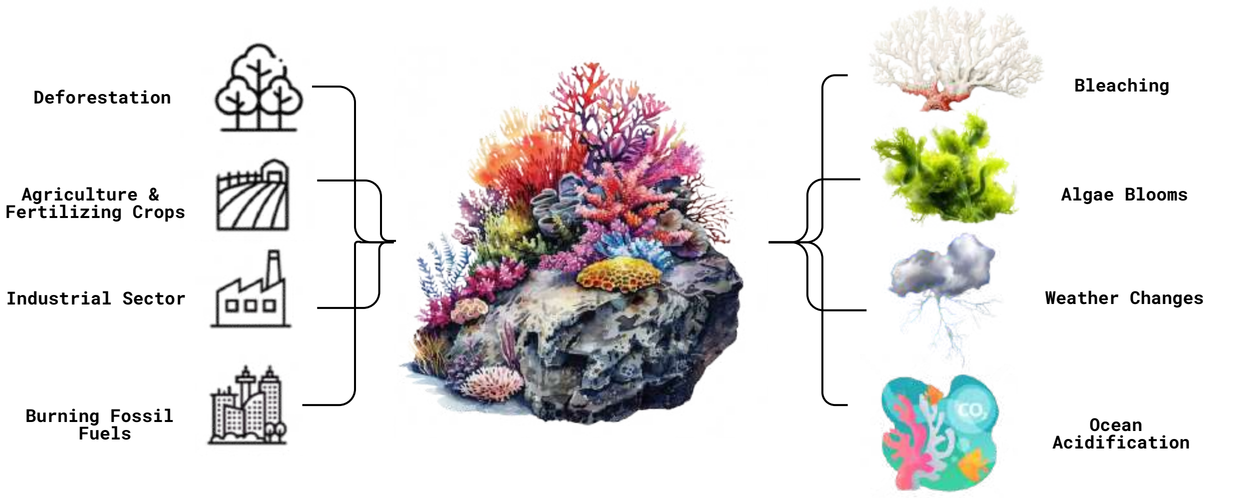
STATE OF THE ART



Introduction

Coral reefs - also known as the 'rainforests of the sea' - are the most vulnerable ecosystem to climate change, seeing a decline of 50% worldwide since the 1950s and projections estimated to rise to 90% by 2050 [1],[5] . The reefs support around 25% of marine life [2]; provide food, coastal protection, and revenue for millions of people [3]; and are a sink for approximately 29% of all CO_2 absorbed by the ocean [4].

Threats to coral reefs are man-made actions that trigger climate change such as deforestation and burning fossil fuels, which indirectly and directly impact the marine environment, causing effects like coral bleaching and algae blooms.



Threats to Coral Reefs

The rapid decline of coral reefs has increased the necessity of exploring interdisciplinary methods for reef restoration. There is an urgency to invest in technology that can help reach ecosystem-scale [1].

Some problems facing current restoration techniques include:

- a difficulty replicating the 3D complexity of coral habitats
- difficulty scaling them to larger areas
- pollution leaching into the environment from toxic objects such as sunken ships or concrete
- a lack of sustainable restoration methods

While reef restoration is not a novel method of conservation, some organisations are utilising 3D printing as a tool for enhancing these efforts.

Thesis Statement

Using advanced manufacturing technology and digital fabrication techniques to design a 3D printed, modular clay structure which aims to promote marine biodiversity in coral reef environments.

3D Printing As a Tool

3D printing with natural materials in conservation is an advancing, yet still niche field that has the potential of being immensely impactful. While 3D printing allows for more complex geometries to be sculpted than traditional methods of structural molding, using natural materials eliminates the use of fossil fuels and provides a hospital environment for organisms to thrive.

Currently, only a few organisations within the marine conservation industry are taking advantage of this novel method of manufacturing. These include RRREEFS, Reef Design Lab and Coastruction, all of whom use natural materials such as clay, oyster shells or beach sand to 3D print reef structures. What these organisations lack however, is a design which caters for enhancing marine biodiversity, not just coral growth.

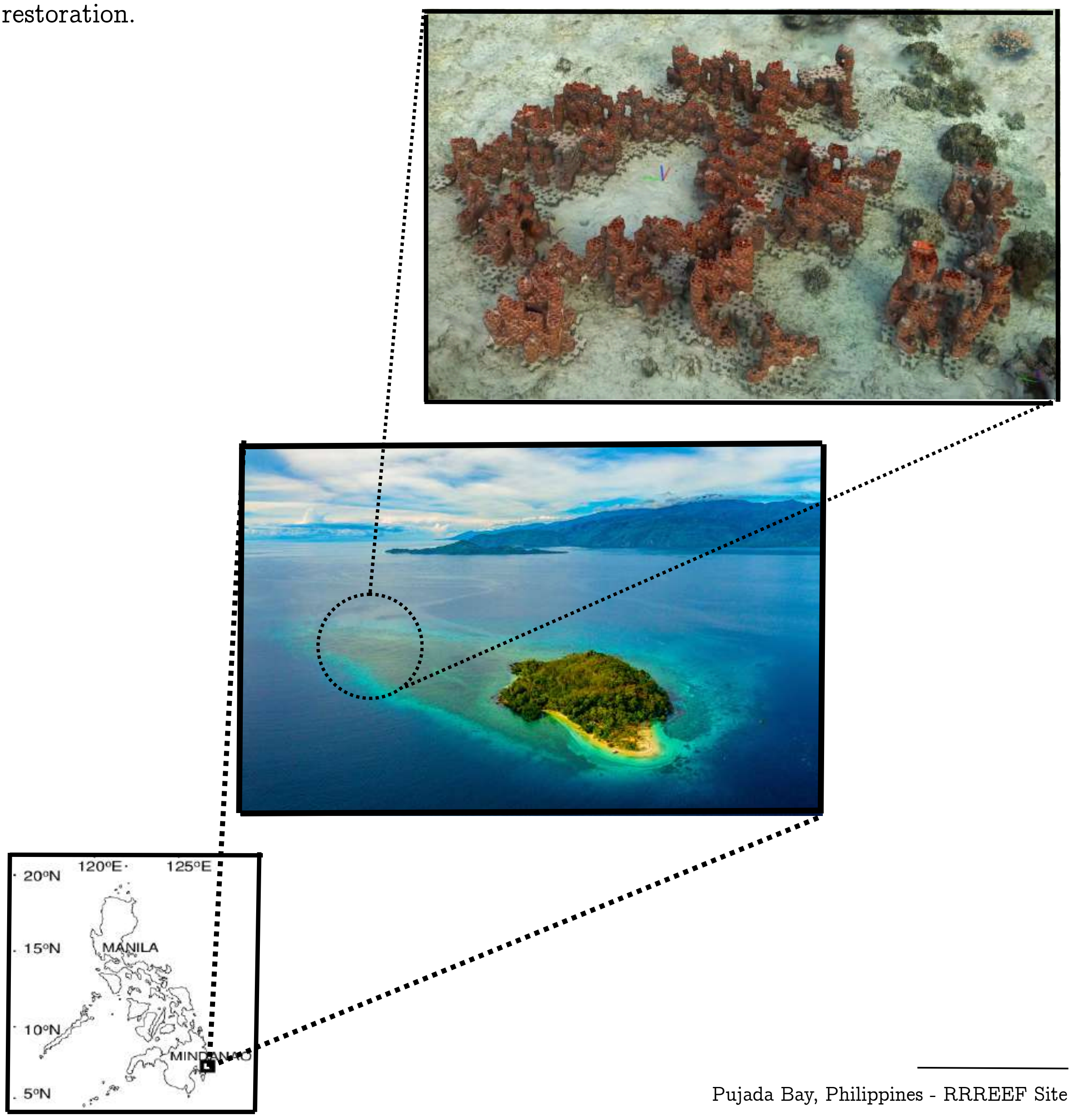


RRREEFS, Reef Design Lab, Coastruction

To design an efficient structure for application within reef restoration it is important to understand that within the natural environment, fish are more abundant in corals with the highest levels of complexity. Reefs therefore, need to be designed for the particular location, environment and organisms [6,] [7]] .

Collaboration & Location

To enable efficient and in-situ testing of TerrAqua, RRREEFS offered to collaborate and test the structure out in their biggest existing artificial reef site at Pujada Bay, Philippines. In February 2024, the site was first constructed, which spans over 100m^2 with 820 3D-printed modules made from terracotta clay. This project has provided a foundation for the marine ecosystem to thrive without further maintenance. Having been declared a marine protected area in 1994, Pujada Bay, with its sheltered waters provides a suitable environment for coral growth and is a biodiversity hotspot of diverse ecosystems. The Philippines is an important location as it contains almost 10% of the world's coral reefs with incredible biodiversity, however, 98% are classified as threatened. It is estimated that less than 2% are still in excellent health status [8]. This data provides evidence for the urgency in which we, as a society, need to develop rapid solutions for reef restoration.



Pujada Bay, Philippines - RRREEF Site

02 |
GEOMETRICAL EXPLORATION

Reef Design Lab - MARS

Triply Periodic Minimal Surfaces

Triply Periodic Minimal Surfaces (TPMS) are defined by their zero mean curvature and locally area-minimizing properties. They are composed of intersecting 2D wavy lines, with an absence of straight lines [1] - an example is the gyroid .

Photo by Wolfram Aplha on "Gyroid" [9]

The gyroid infill pattern used in 3D printing is known for its great strength to weight ratio as it provides excellent load bearing capabilities. Gyroid shapes are also highly efficient in terms of material usage - the interlocking channels and lattice pattern decrease the volume of material, which minimises material waste. Combining the gyroid structure with 3D clay printing for the purpose of coral reef restoration would provide an excellent solution to the problem stated. The geometry consists of varying heights, channels, platforms and a high surface area which provide a beneficial habitiat for a thriving marine environment.

A designer who has utilised the gyroid structure in conservation is Alex Schofield, as part of the Buoyant Ecologies Float Lab, he created these hanging prototypes - 3D printed using calcium carbonate. Titled 'Hanging Fish House', they are computationally designed providing spatial alcoves for a range of marine life [9].

Photo by Olupsi on "Hanging Fish House" [10]

Fischer-Koch-S (FKS) are another type of triply periodic minimal surface (TPMS). In the research paper [11] FKS scaffolds were fabricated in ceramic and compared against a Gyroid surface structure for the potential application in bone tissue engineering.

The results showed that FKS scaffolds were:

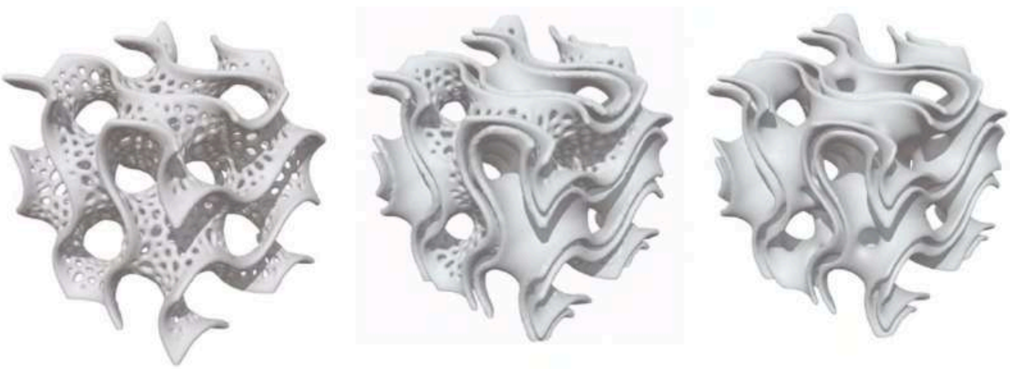
- 32% stronger
- absorbed 49% more energy
- had 11% lower permeability

when compared to the Gyroid scaffolds manufactured at 70% porosity. TPMS have a high surface-to-volume ratio and interconnected porous structures which optimise cell attachment, making them ideal structures to consider for artificial coral reef.

Photo by Thangs on "Dave Makes Stuff - Fischer" [12]

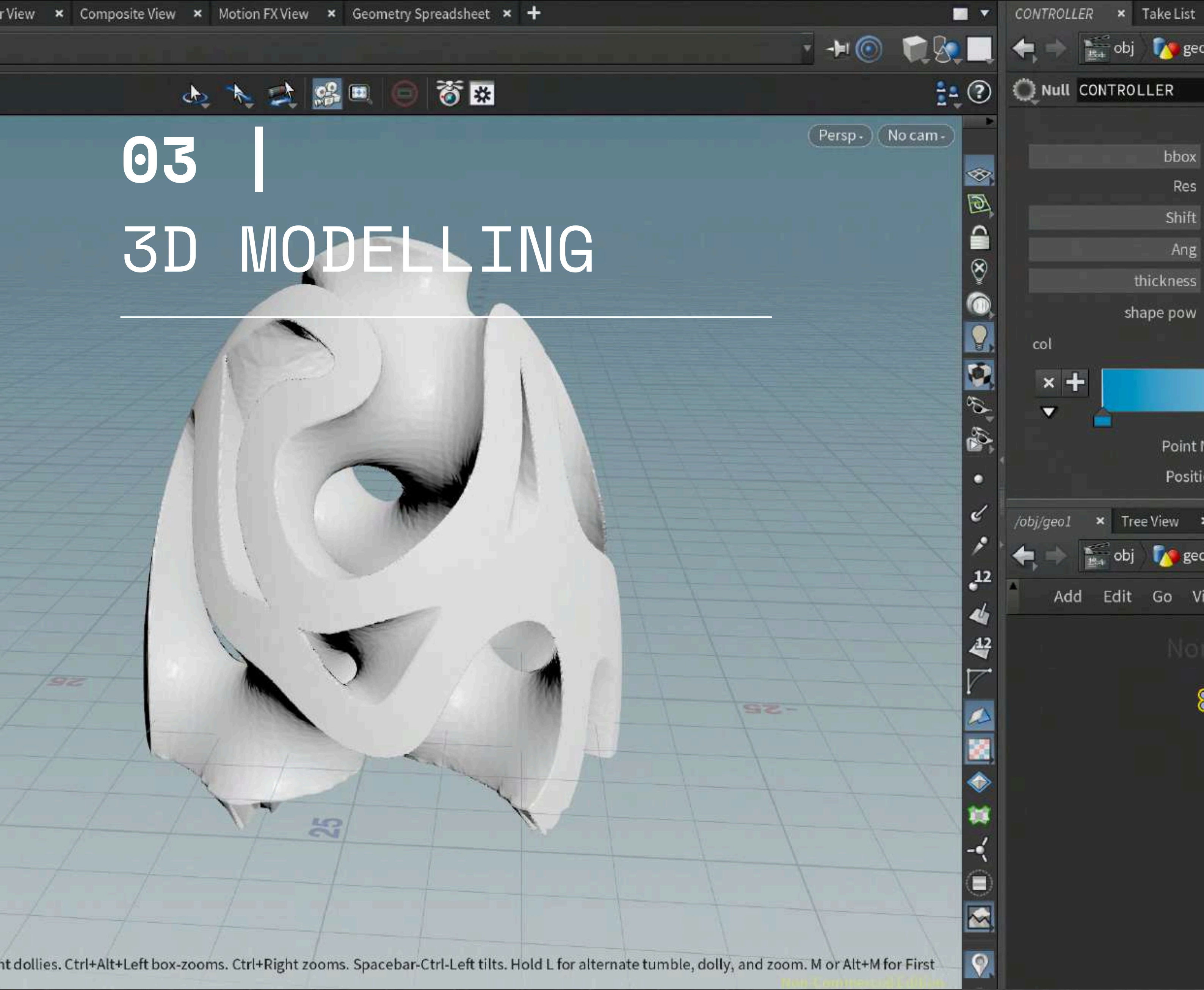
Voronoi

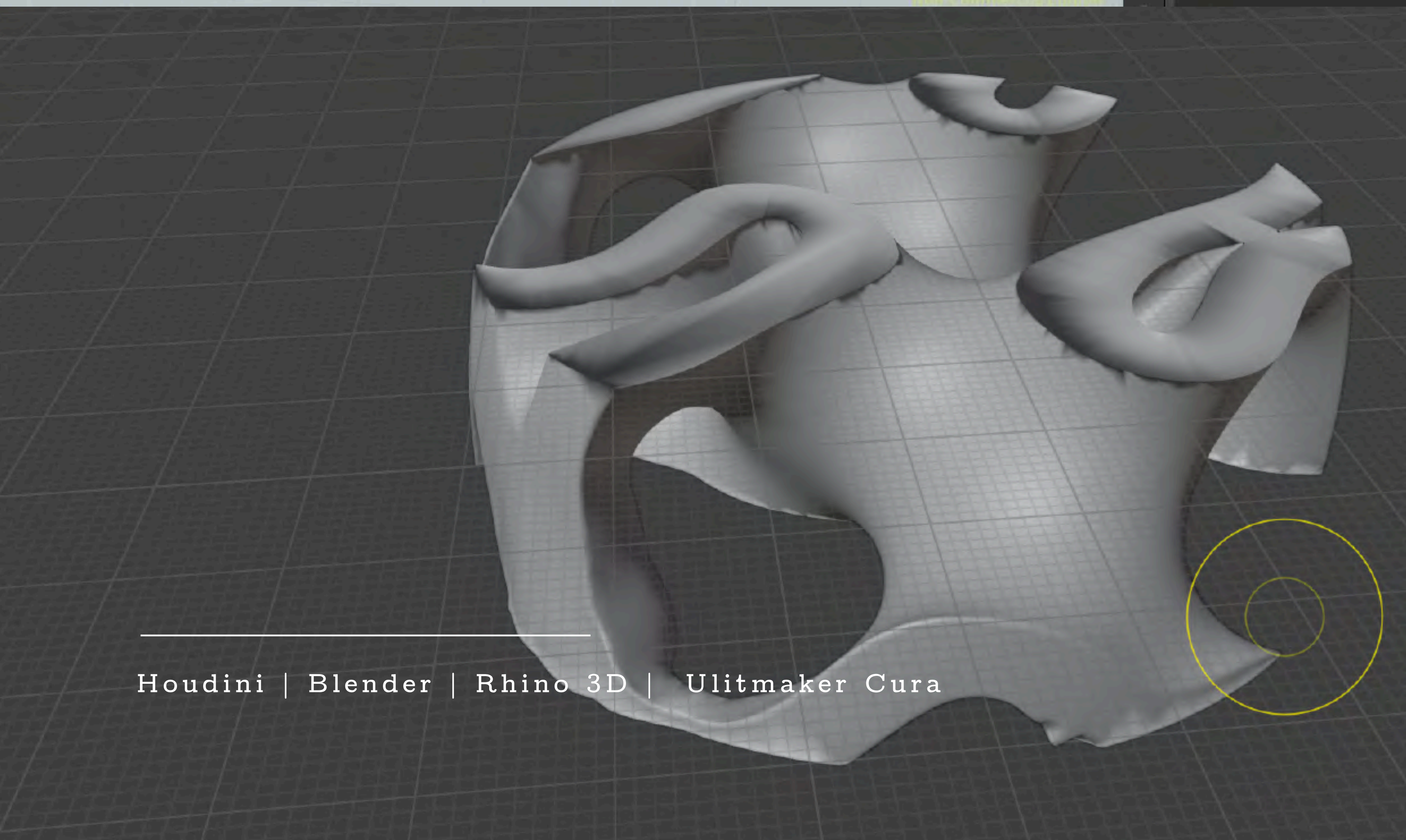
A Voronoi pattern is a type of tessellation in which a number of points scattered on a plane subdivides in exactly n cells enclosing a portion of the plane that is closest to each point. Presented below are a few models from Thingiverse [13], which combine both voronoi and gyroid structures - these have the potential to make an efficient artificial coral reef structure. It would be interesting to explore whether these structures could be made into a modular piece that slots into another to create a unit.



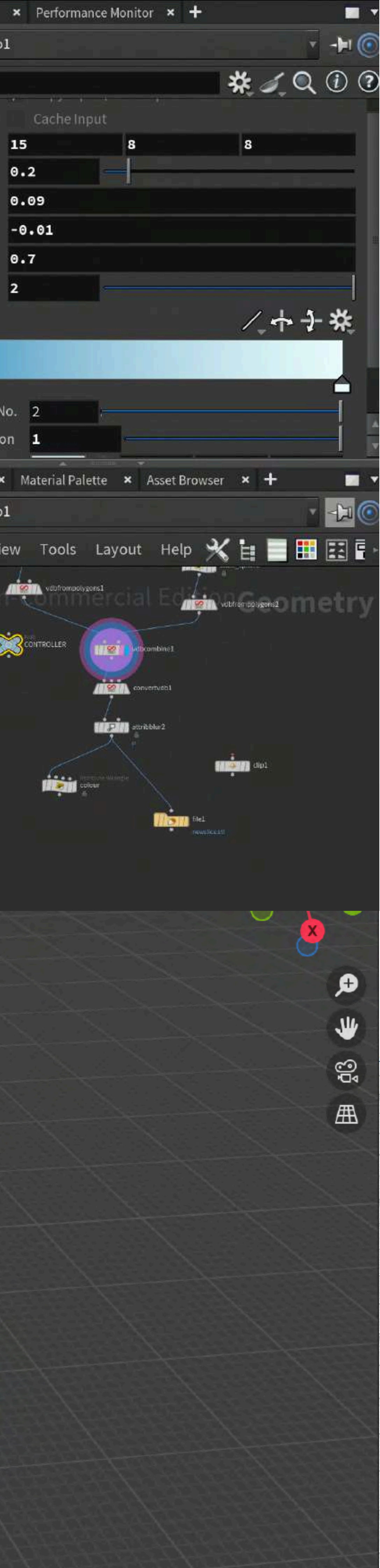
A Single Gyroid Surface in a Voronoi Pattern | Two Offset Gyroid Surfaces - one solid, one voronoi | Two Solid Offset Gyroid Surfaces Connected With 'Wormholes' [13]

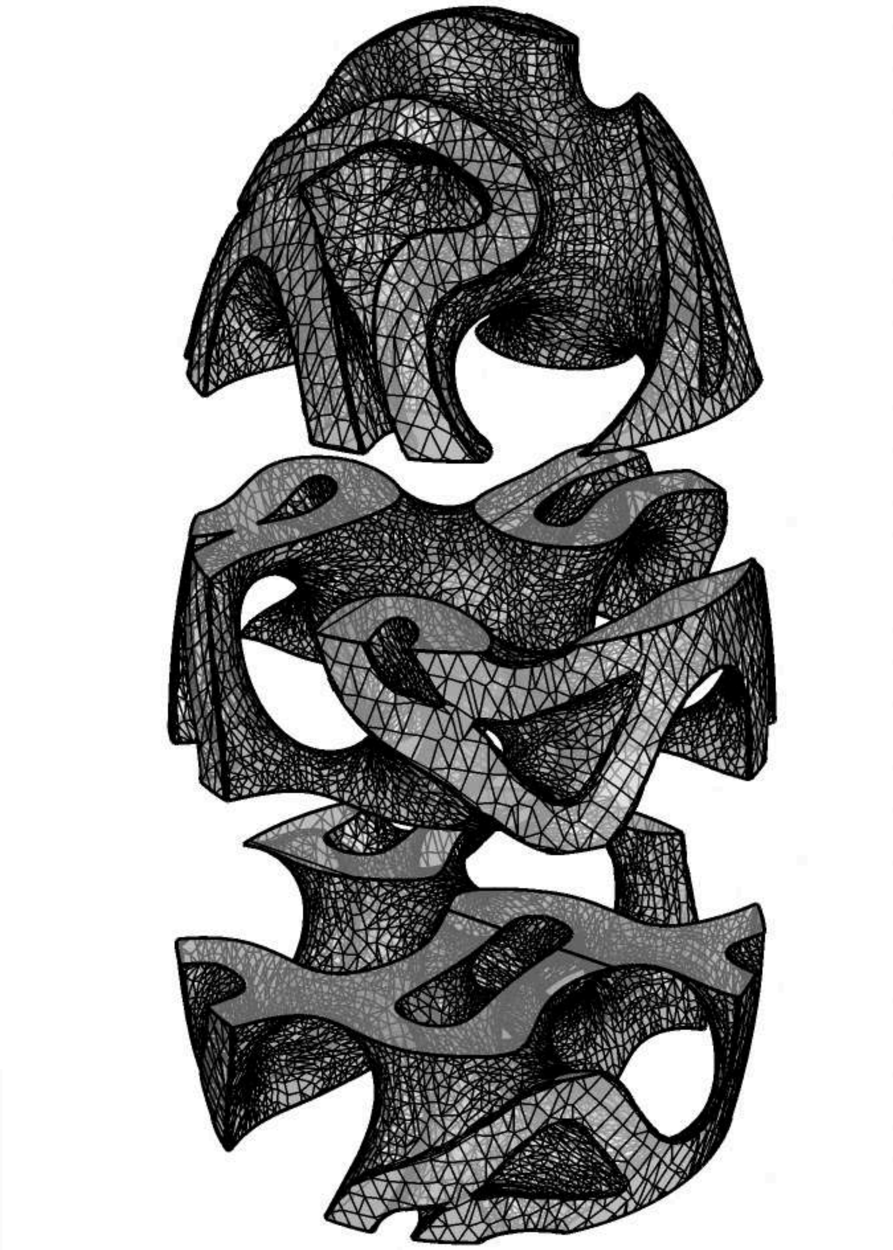
03 |
3D MODELLING

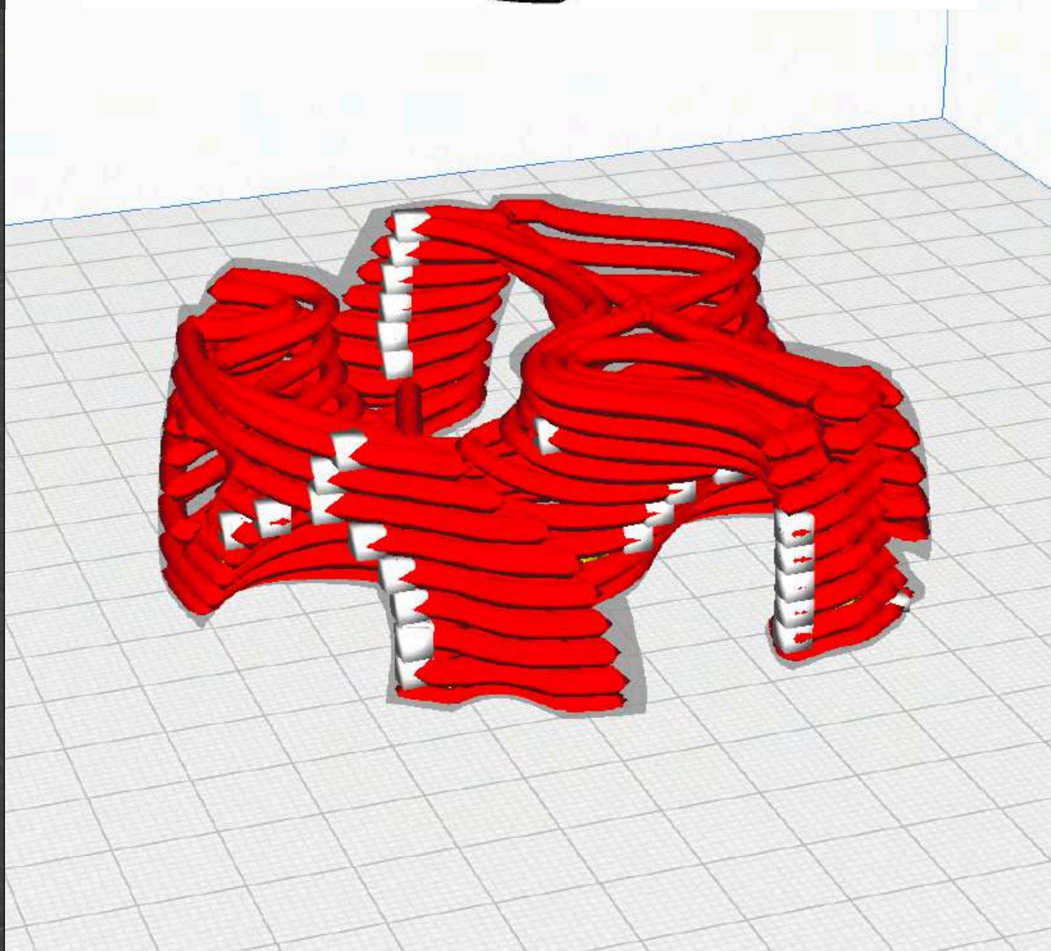




Houdini | Blender | Rhino 3D | Ulitmaker Cura

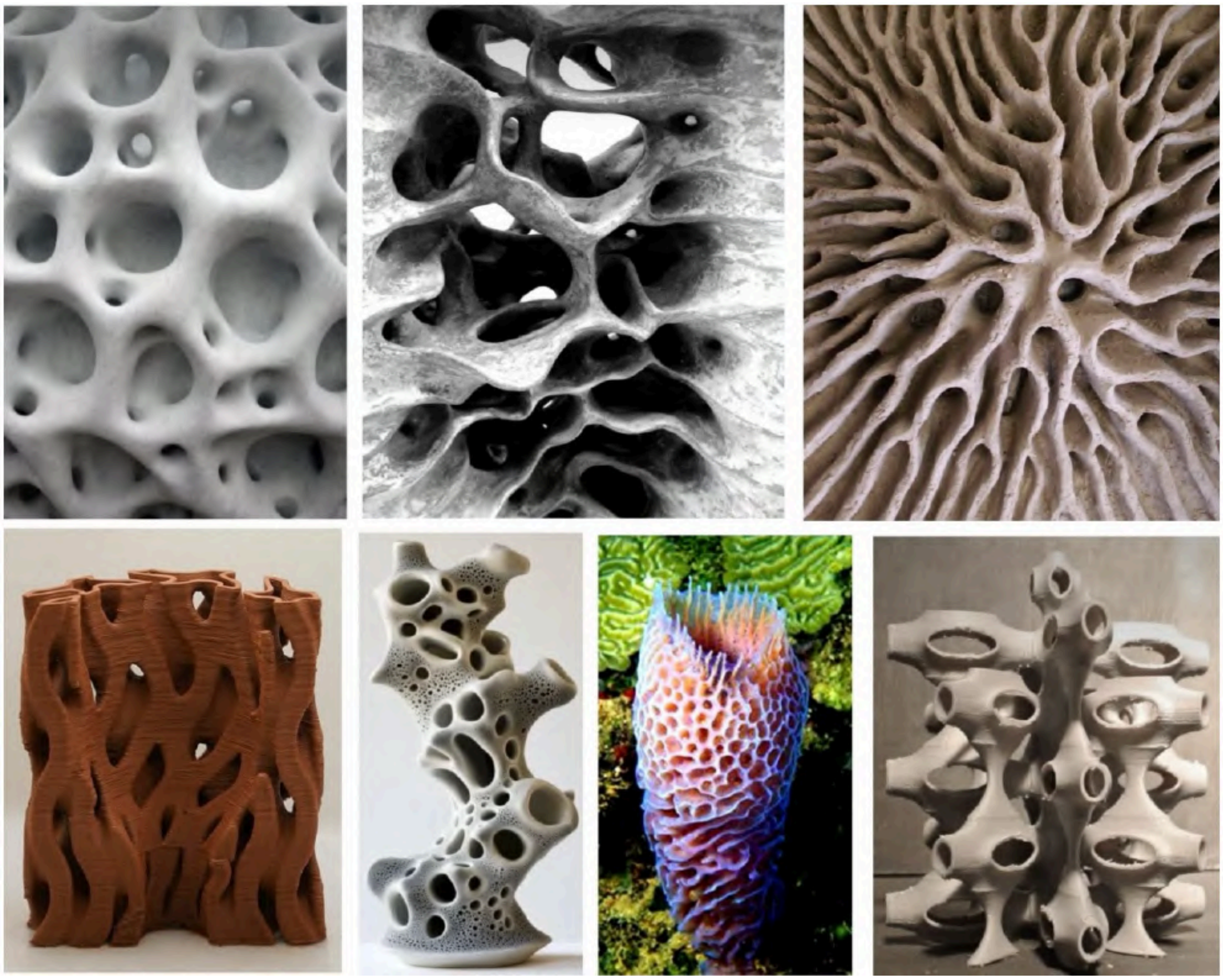

Performance Monitor
Cache Input
15
8
8
0.2
0.09
-0.01
0.7
2
No.
2
on
1
Material Palette
Asset Browser
Tools
Layout
Help
Geometry
vdbfrompolygons1
vdbfrompolygons2
CONTROLLER
vdbcombine1
convertvdb1
attribblur2
clip1
colour
file1





Inspiration

Taking inspiration from nature where mathematical surfaces such as gyroids and voronoi can be found and developing a modular organic design could create an ideal habitat for marine life and coral attachment. Combining these elements would promote complex geometries, high surface area and varying heights and channels. Fractal geometry and porous architecture in nature were also found to be particularly interesting, such as in adaptations that cooled down surfaces such as mangrove roots and termite mounds.



Inspiration [14] | [15] | [16] | [17] | [18] | [19] | [20]

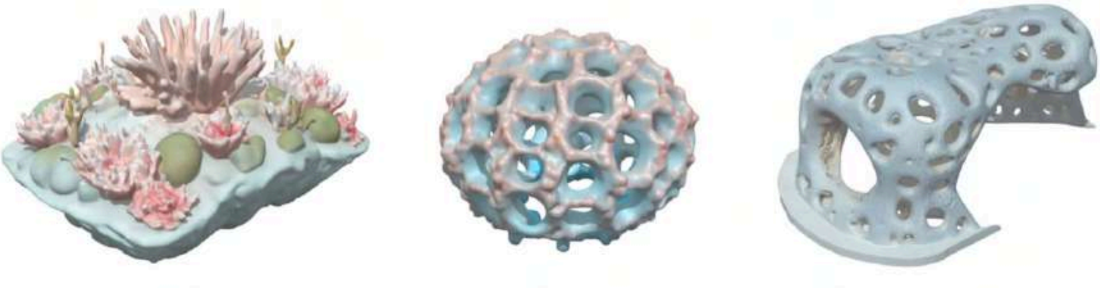
AI Generation

Using the 3D AI software, Tripo3D , some models using prompts were generated with the aim of satisfying the following conditions:

- complex geometry for maximum marine biodiversity
- high surface area for greater potential of coral polyp attachment
- modular unit to allow for customisable construction
- not many fragile extensions
- relatively uncomplicated 3D printing process i.e. how much support does it require

With key words such as 'parametric', 'organic/biomimetic' and 'gyroid', the initial models below were generated. The designs which had a lattice structure were particularly interesting, however, this would be difficult to achieve with clay 3D printing.

One of the initial structure ideas involved designing a modular pavillion, with the concept being that it would generate more shade and shelter that could potentially cool surrounding waters. The final model below consists of 2 layers of surface, allowing for more alcoves and channels to form which would be great in this application. A struggle with this would be 3D printing the overhangs - so the orientation in printing is incredibly important.



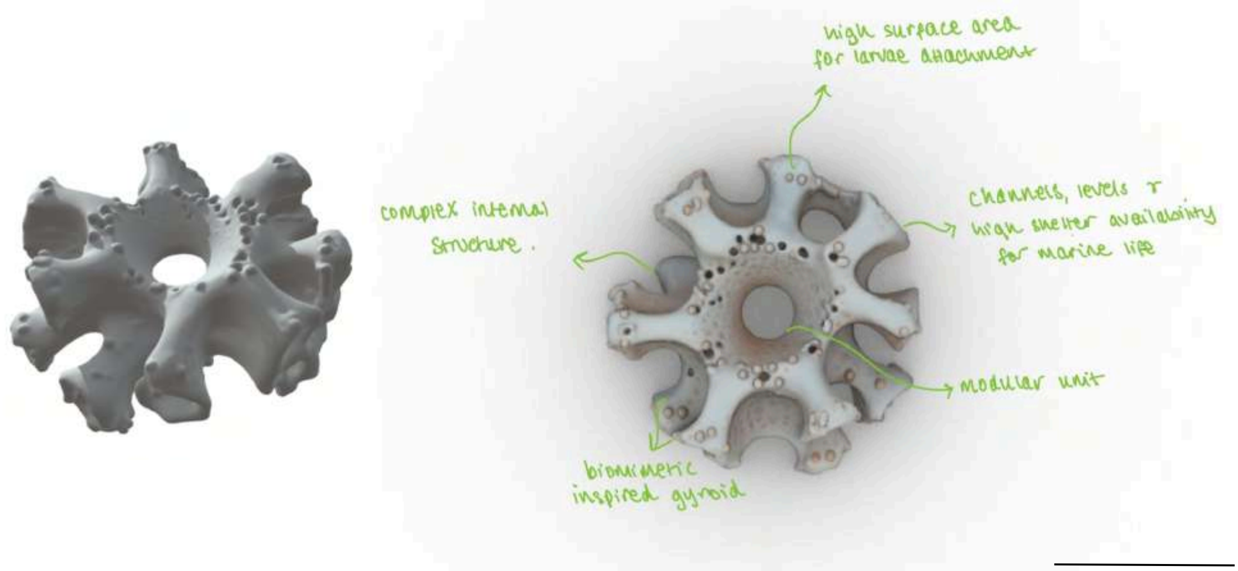
Tripo3D AI Generated Models 1.1

Adapting the prompts to include the key words 'termite mound', 'roots' and 'tower' produced the models below.

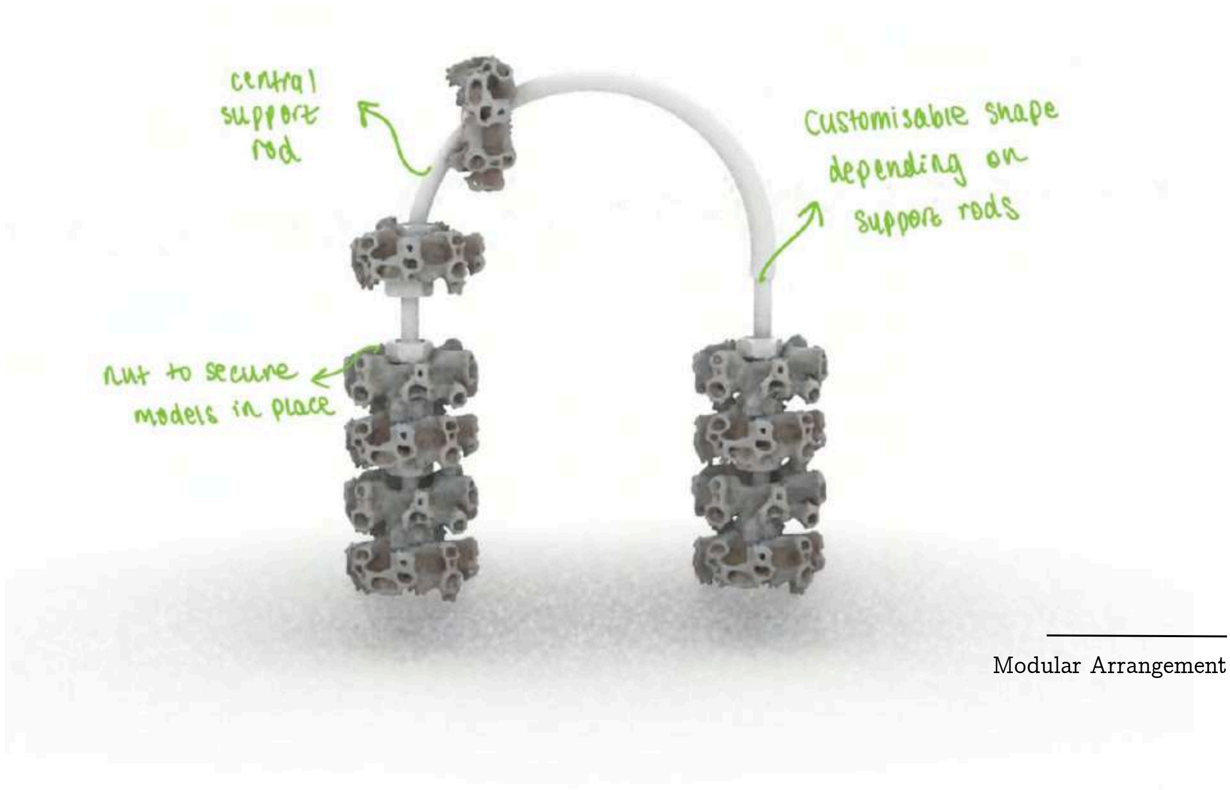
Tripo3D AI Generated Models 1.2

The left model's roots could be printed as one or in multiple parts with additional modules slotting in (similar to how the flower-like growths have formed in this model). The root structure would allow for dynamic water flow and plenty of crevices/ridges for larvae to get caught in. The model on the right sparked inspiration from russian doll toys. What if a structure was designed which could be comprised of say 2 separate layers each one varying in complexity and width of holes? Imagine the inner most surface being a Fischer Koch S column, the second surface which you could place over this column could be a voronoi-like structure with larger holes. This would provide a variety of habitats in a singular unit, whilst channeling water flow and producing a high surface area for larvae attachment.

The model that was most applicable due to the varying heights, channels and surfaces, is shown below . A modular piece can be visualised by slotting multiple pieces through a bar, stacking one on top of another.



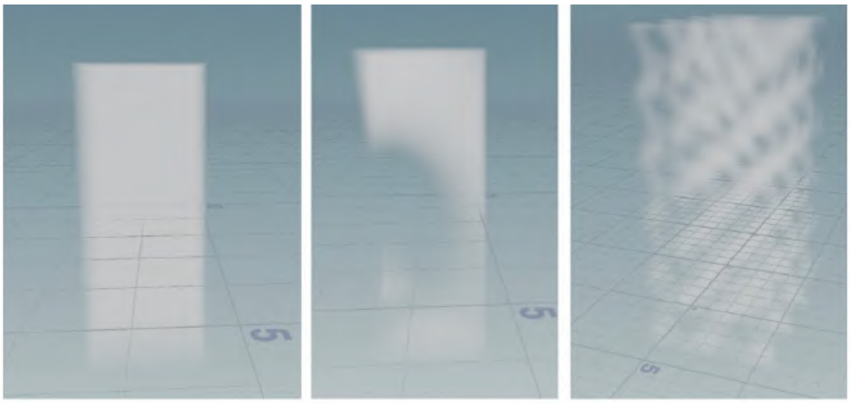
Tripo3D AI Generated Models 1.3



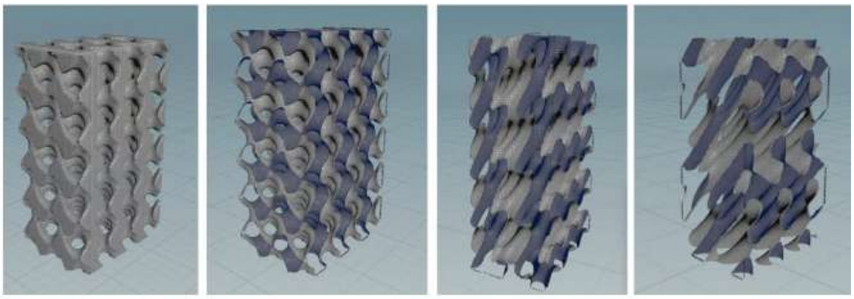
Modular Arrangement

Houdini

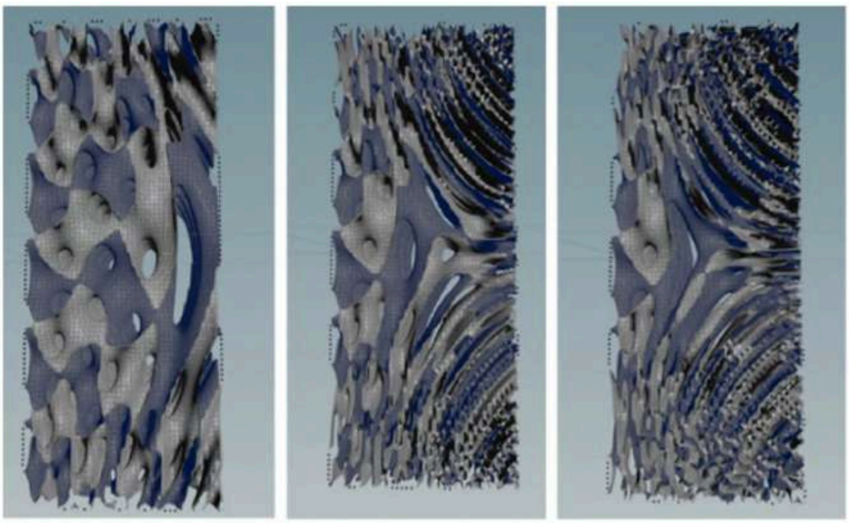
A tutorial on 'Deformed Gyroids using Houdini' [21], provided a great base for exploration into the desired geometry. As stated previously the triply periodic minimal surface would both look visually appealing and provide a great habitat for the growth of an underwater ecosystem. The gyroid structure was chosen based on the resources available to learn the Houdini software.



Creating Gyroid Surface



Controlling Desnity (Res) | Parameter Shifting | Rotational Shifting | Angular Shifting



Resolution: 1.0
Shift: 0.0
Angle: 0.1

Resolution: 1.0
Shift: 0.0
Angle: 0.4

Resolution: 1.0
Shift: 0.0
Angle: 0.7

Combined Deformation

The first iterations of this design are shown below, as you can see the curves are very complex and not suitable for clay 3D printing. In order for the print to be valid and also not require supports, the angles of the curve must not exceed 30 degrees.

Resolution: 0.481
Shift: 6.43
Angle: 0.15
Thickness: 0.15

Resolution: 0.481
Shift: 1.41
Angle: -0.205
Thickness: 0.1

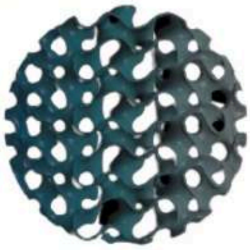
Resolution: 0.481
Shift: 6.43
Angle: -0.1
Thickness: 0.15

Resolution: 0.313
Shift: 1.66
Angle: -0.13
Thickness: 0.1

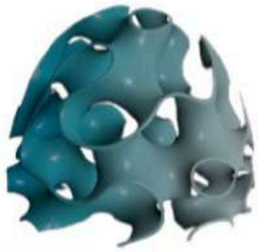
Initial Iterations

After some alterations within the 3D environment, the second iterations resembled the idea that was trying to be generated.

Bounding Box: 4 x 8 x
Resolution: 0.34
Shift: 0.02
Angle: -0.016
Thickness: 0.1



Bounding Box: 4 x 8 x 8
Resolution: 0.544
Shift: 0.02
Angle: -0.259
Thickness: 0.1



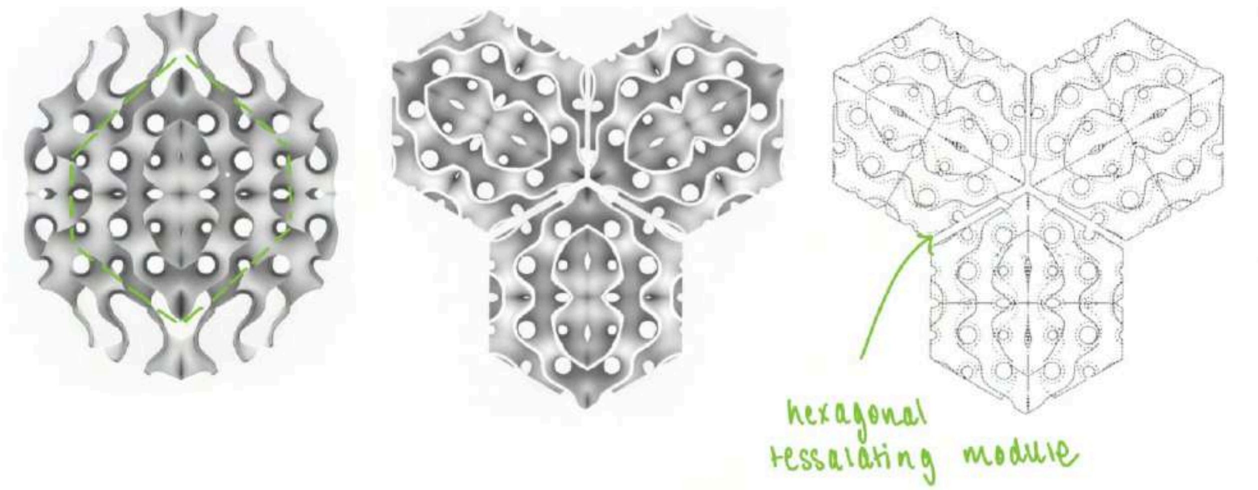
Bounding Box: 11 x 8 x 8
Resolution: 0.3034
Shift: 0.12
Angle: -0.033
Thickness: 0.1

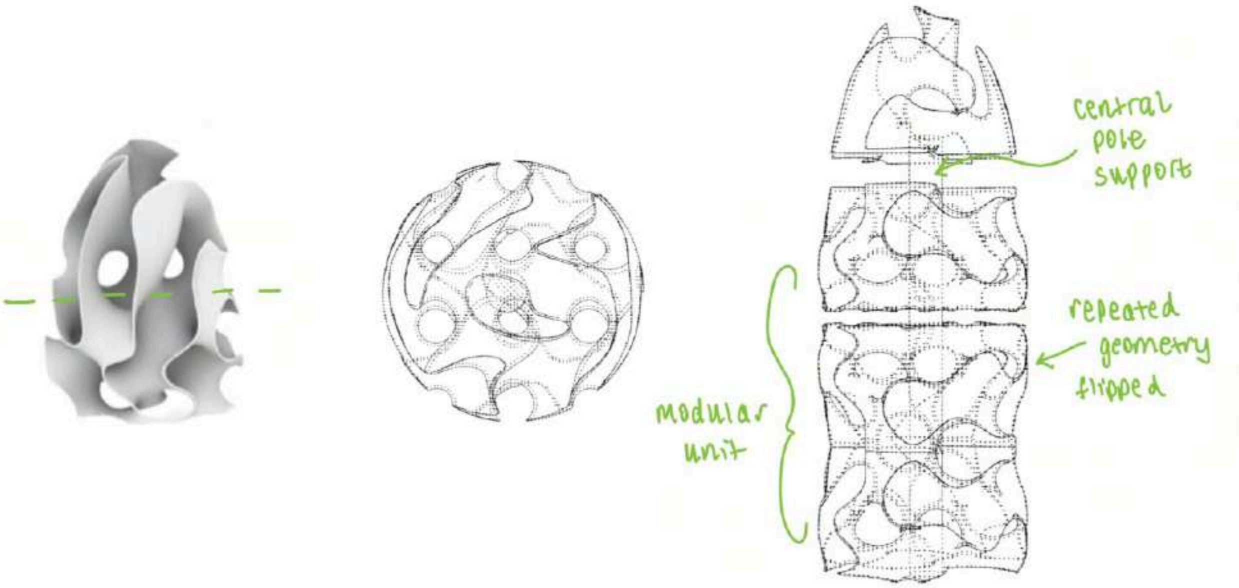
Bounding Box: 4 x 8 x 8
Resolution: 0.303
Shift: 0.1
Angle: -0.033
Thickness: 0.1

Second Iteration

Modular Explorations

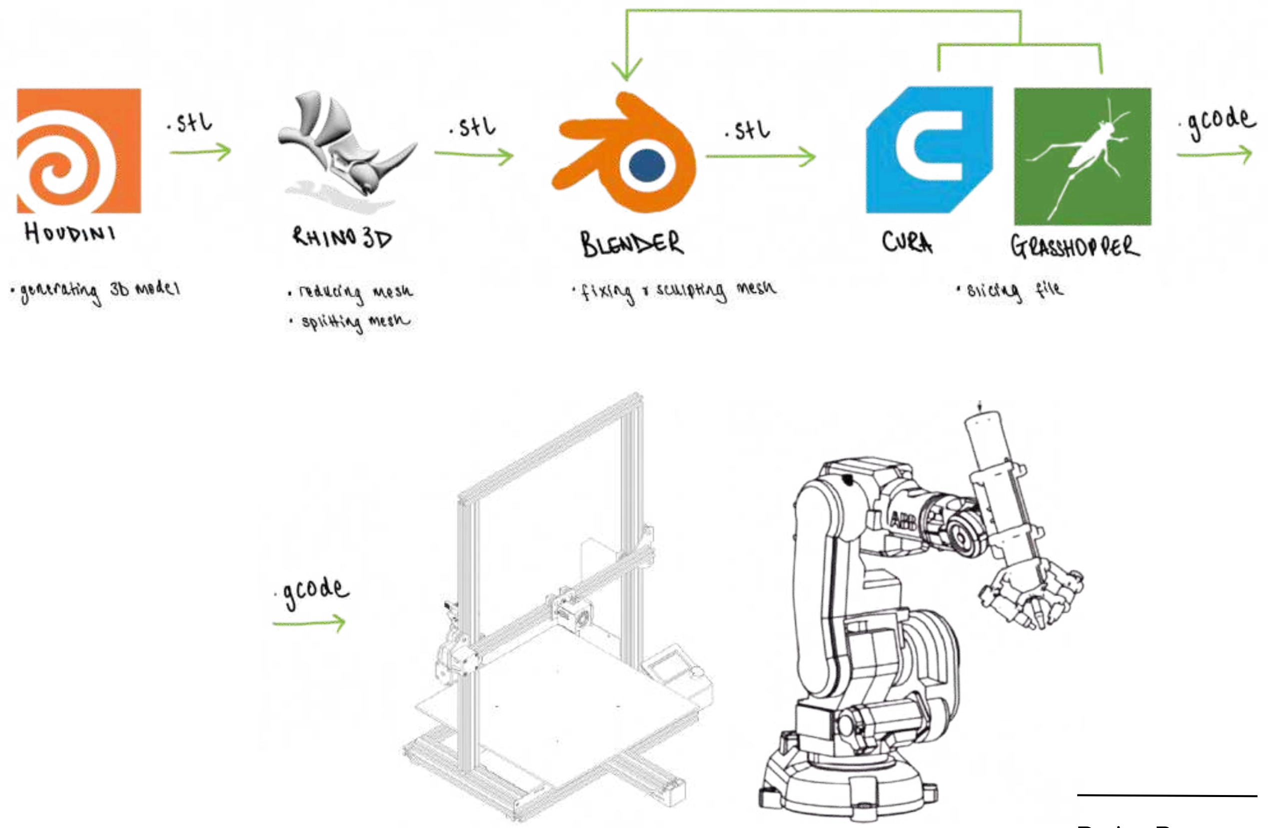
Modularity is important for this application as when deployed an artificial reef it is necessary that the structure is easily transportable and easy to assemble underwater. Initially, two modular designs were generated: the first being a tesseleting 'pavillion' made out of hexagonal pieces; and the second being a stacked tower. The latter was chosen as it produced more complex geometry and one could build many towers with different heights allowing for a varying landscape. The pavilion lackced this as the height across would remain much the same.





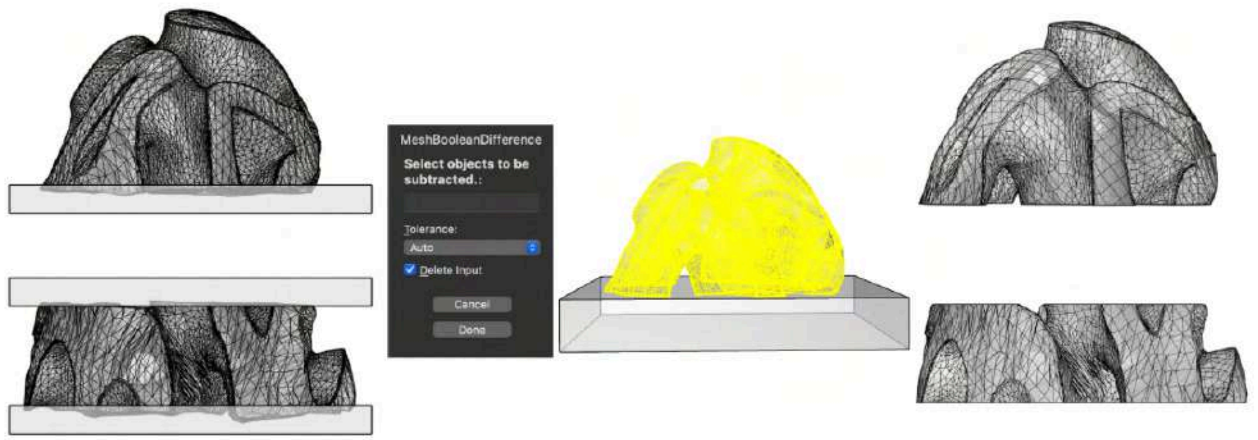
Modular Designs

After developing the 3D model in Houdini, the process for refining the structure to be ready for 3D printing is shown via the following steps:



Design Process

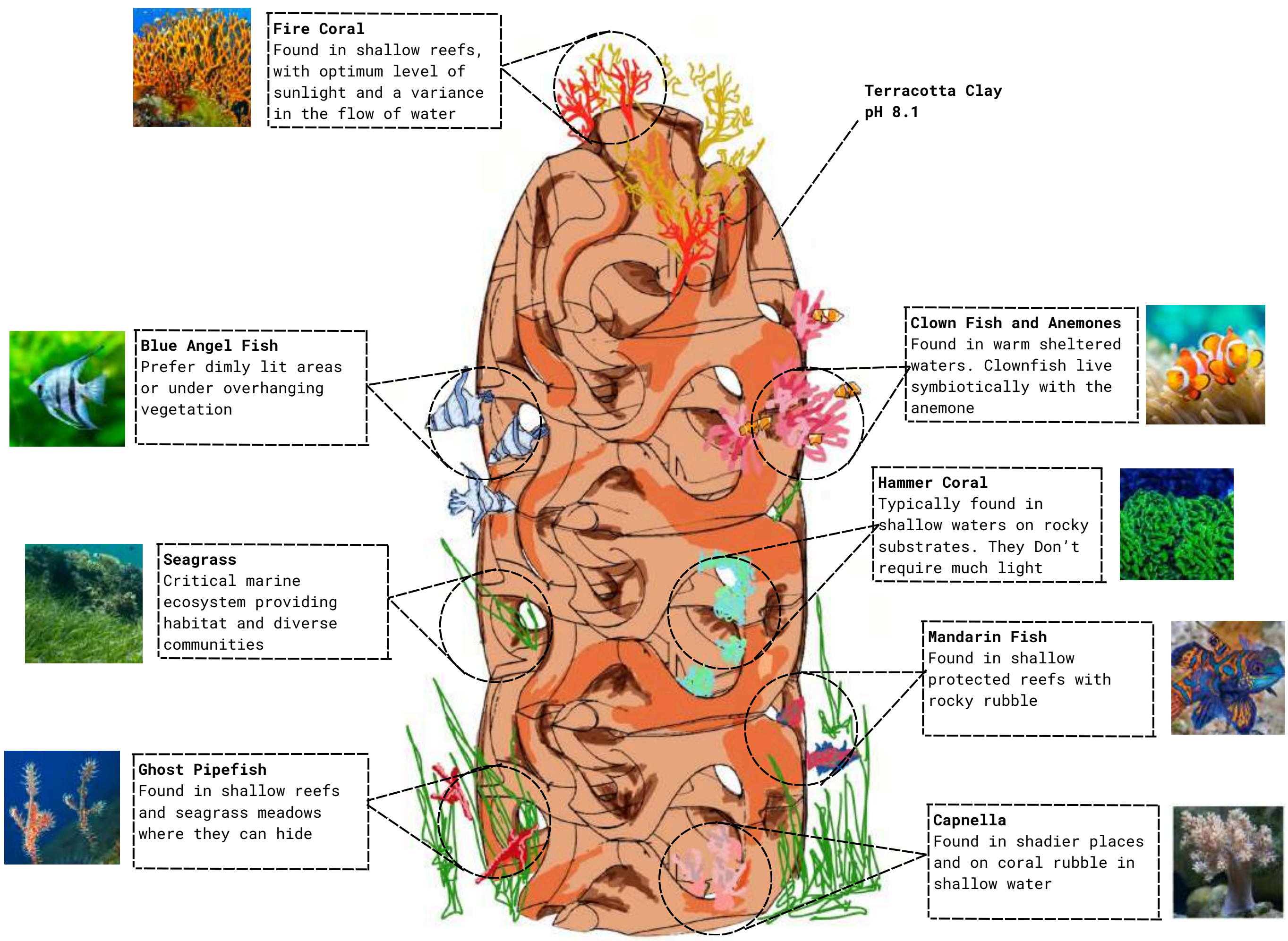
To split the Houdini mesh into modular parts required using the Rhino 'mesh boolean difference' tool. After this step further mesh editing was carried out in Blender to ensure that the overhangs and channels would not fail whilst being 3D printed.



Splitting Mesh in Rhino 3D

Future Ecosystem

As stated in chapter 01: State of the Art, ‘reefs need to be designed for the particular location, environment and organisms’. So, after selecting a few of the many Filipino coral reef organisms, a future ecosystem was developed to portray the habitat that the proposed structure could create. These organisms thrive in a variety of spaces and environments which my design caters for.



Terracotta Clay [22]

04 | MATERIAL FABRICATION

Terracotta Clay

Terracotta clay - meaning 'baked-earth', is 100% natural and has great porosity with a 95% recyclability rate [22]. It was advised to use this material by RRREEFS due to these properties.

To make the clay viable for 3D printing meant a lot of trial and error however eventually it was found out that one should aim for around 6% of water content within each mixture of clay i.e. for 1kg of clay add 60g water.


Clay 3D Printing[23], [24]

Waste Oyster Shell Composite

Oyster shells are a great source of Calcium Carbonate ($CaCO_3$) with a content up to 95%. Originally it was thought that combining this waste material into the structure would enhance the strength, porosity, durability, and also provide a similar skeleton to coral reefs for polyps to attach onto.

Some organisations which have developed materials using shells include Oyster Matter [25] who experimented with ground shells and natural binders. Marine Eco Bricks [26], who 3D printed with a composite cement and utilise recycled oyster shell powder as a subsitute for sand and gravel, reducing cement consumption and lowering carbon emissions. This project was designed to enhance shoreline protection. Finally, the research highlighted in article "Oyster Shell Waste as Reinforcement for Clay" [27], stated that compared to pure clay samples, the oyster shell reinforcement enhances the compressive and flexural strength of the composite by 26.5% and 34%, respectively at 1150°C sintering temperature. This specific 3D printer could print with overhanging angles of 32°, and bridging length of 8 mm without any support requirement. With this research it seemed possible to develop an oyster shell and terracotta clay composite.


Oyster Shell 3D Printing[28]

Oyster Shell and Clay Gyroid Prototype

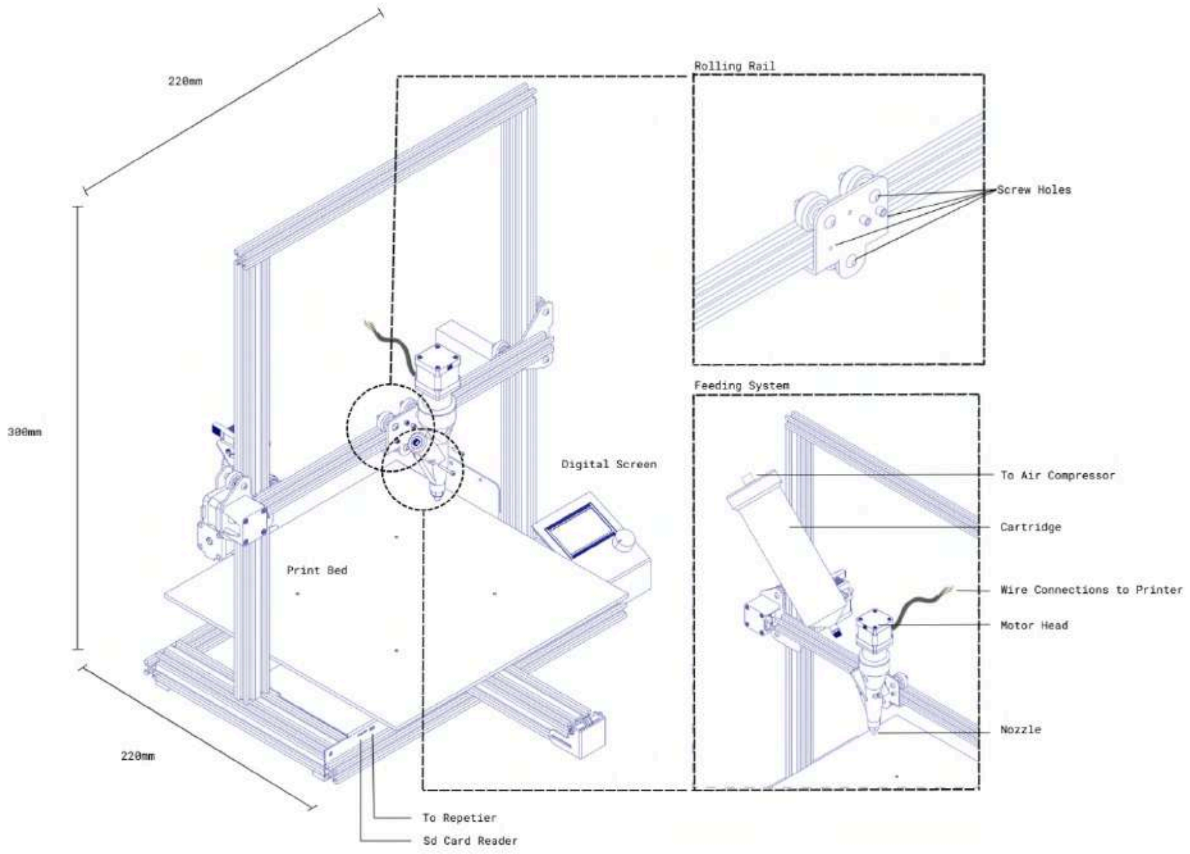
05 |

3D PROTOTYPING

3D Paste Printer

The first experiments with the paste printer were used to test the correct flow and consistency of the material, along with the behaviour when overhangs are introduced. The paste printer available at IAAC/Fab Lab Barcelona was the Creality Ender 5, which has the following characteristics:

- Cartesian machine with an exterior footprint of 440 x 410 x 465 mm and a print build volume 220 x 220 x 300 mm which offers a larger print volume.
- The box-like frame offers better stability during printing.
- The bed only moves vertically (Z-axis), reducing potential print errors tied to Y-axis movement. Due to improvements in stability and Y-axis design, it can print faster without sacrificing quality.
- Resume printing function (in case of accidental unplugging).
- 24V-350w branded power supply to stand future modifications/upgrades.



Paste Printer Setup

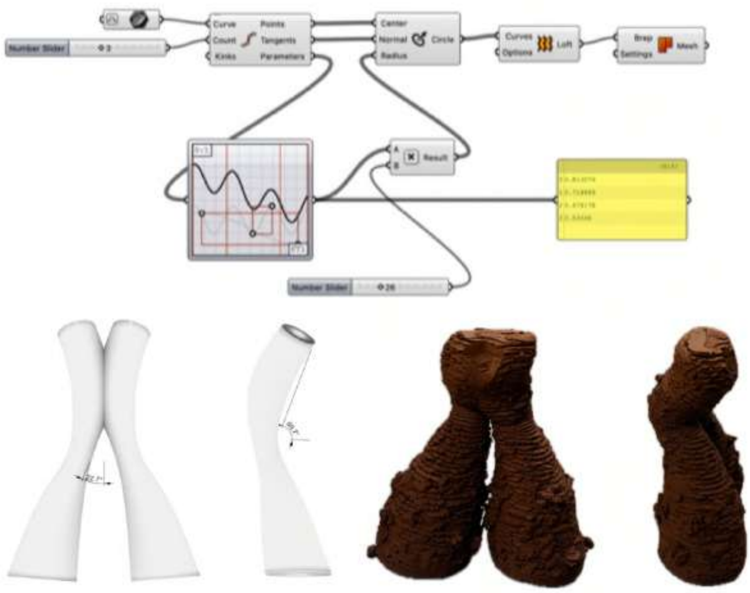
The system works with air pressure for the feeding system and a motorized controlled extruder head. The feeding system part is connected to the rolling raile with 5 screws which makes it easier and faster to clean during disassembly. The cartridges are industry-graded HDPE pressurized (300cc-500cc) and safe up to 100PSI 6.9 bar (normal working pressure is 2-4 bars). A silent air compressor of ~55 db with a rating up to 6 bar and 3l deposit with regulating valve and safe release is also used.

Repetier is a software which is used to control the parameters of the extrusion, a Feedrate of 40 and Flowrate of around 180 worked well. The air pressure machine was always set to around 2-3 Bars. Another key value was the layer height which was set to 1.5mm in Cura, with an initial layer height of 2mm.

3D Clay Tests

Repetier is a software which is used to control the parameters of the extrusion, a Feedrate of 40 and Flowrate of around 180 worked well. The air pressure machine was always set to around 2-3 Bars. Another key value was the layer height which was set to 1.5mm in Cura, with an initial layer height of 2mm.

The maximum overhang that a clay structure can have is 30°. With this in mind, some prototypes were designed to understand the behaviour a bit more when holes and overhangs are introduced.
Following a Rhino Pipe tutorial [29], provided information on how to generate structures using the Sine Summation Graph Mapper.



Grasshopper Script and Pipe Prototype

The next test involved exploring how a hole in the centre affected the strength of the structure. Here, it was ensured that the central hole did not exceed a 30° angle. The resulting structure was very supported and stable.

Central Hole Prototype

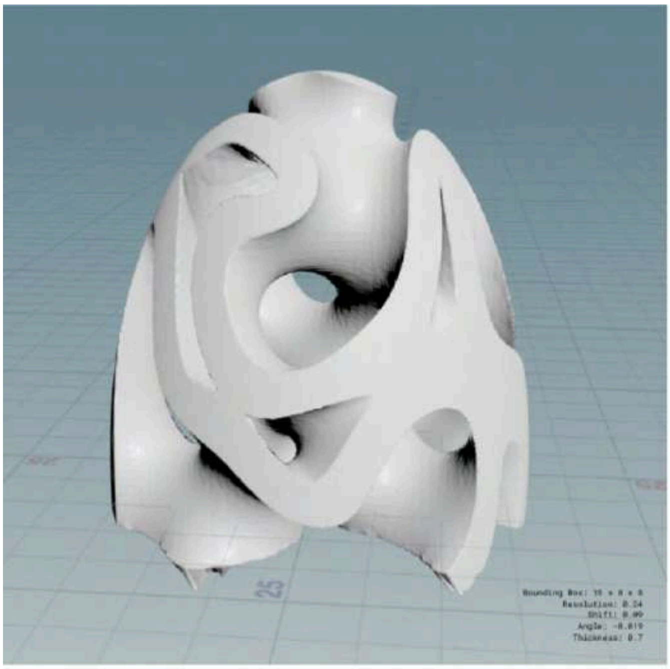
The following test aimed to understand whether the size of a circular hole created an unstable structure or affected the formation of other holes. Each hole maintained a good structure throughout printing apart from the top left one. The reason this hole collapsed was due to the wall to the left of it being too thin to support the increasing load above it.

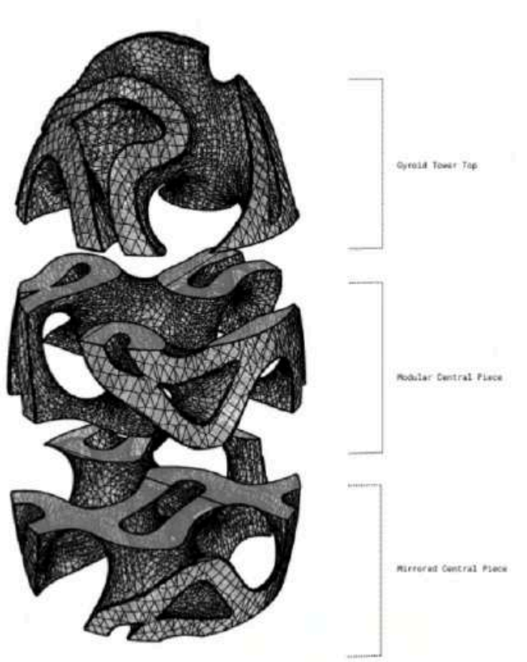
Multiple Hole Prototype

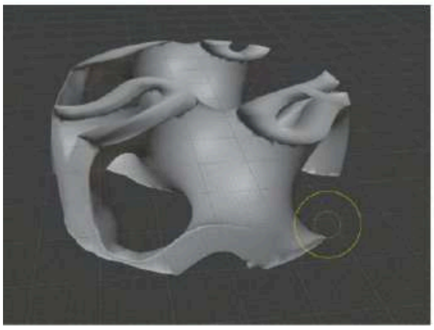
Clay Gyroid

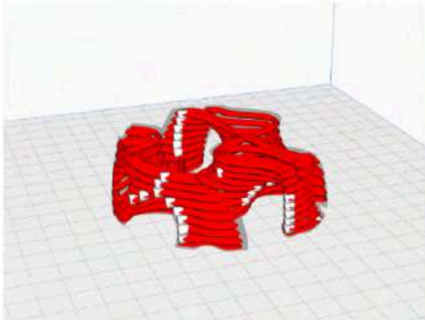
The first clay gyroid tests explored how layer height and water content affected the print. Initially, the layer height was 3mm with a water content of 3%, which turned out to be too wide and dry. It was found that an ideal layer height was around 1.7mm with a water content of 7%.

3mm, 3% | 3mm, 5% | 1.5mm, 6%









Workflow Process: Model Generation in Houdini | Slicing and Refining in Rhino | Sculpting in Blender | Slicing in Cura | Printing

Clay and Oyster Shell Gyroid

After grinding waste oyster shells into a fine powder, they were incorporated into the clay mixture at a 1:3 ratio. The prototype shown below was mixed with 140g of water. During printing it was noticed that some overhangs were still too steep and narrow cuasing the print to nearly collapse - these faults were fixed in the Blender model afterwards.

Layer Height: 1.5mm | Scale | 127 x 127 x 39mm | Print Time: 2 hours |

After adjusting some settings and adding more water to the mixture, the top module was printed. The structure printed more smoothly and faster with no noticeable points of failure.

Clay and Osyter Shell Powder Prototypes

06 | TESTING


Kilned Oyster and Clay Gyroid

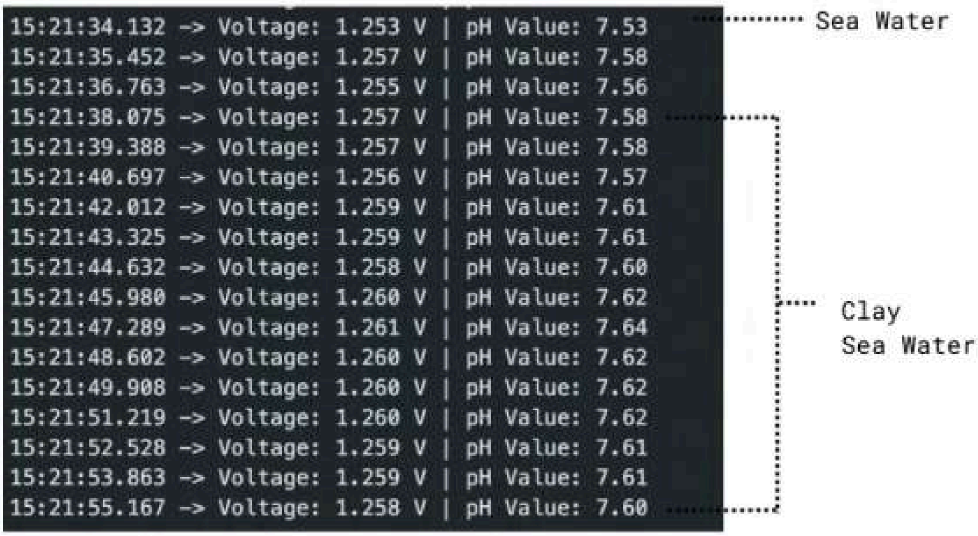
Firing

After firing the oyster shell and clay composite, the structure completely crumbled suggesting the oyster shells did not add structural integrity after all. This mixture cannot be used for the desired application so it was decided to adjust the research project to be purely focused on generating a structurally sound 3D model using only terracotta clay.

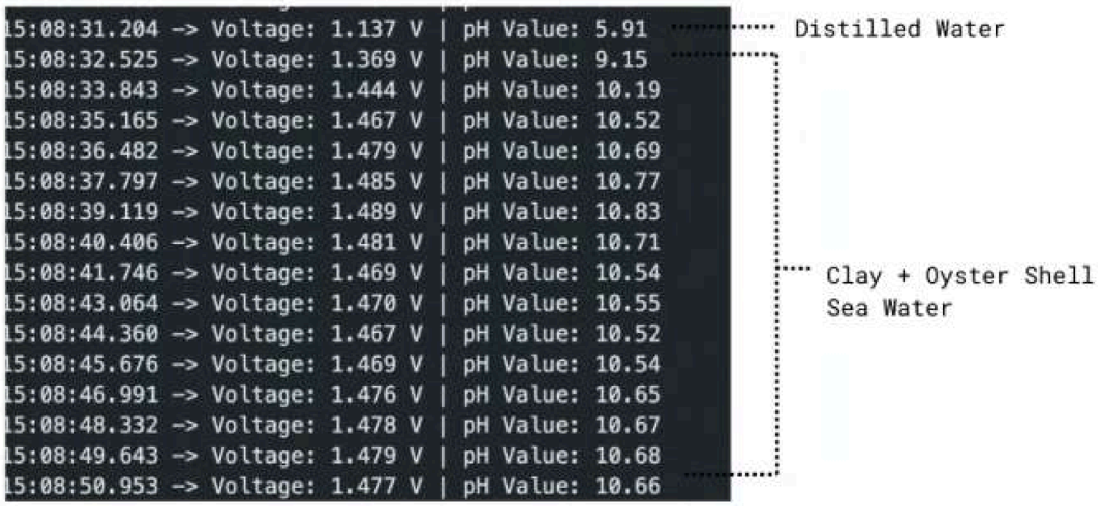
Kilned Clay and Osyter Shell Powder Prototypes

pH

RRReefs mentioned that the pH of the water in Pujada Bay, Philippines was 8.1, and the material should not affect the environmental conditions. Therefore, using Arduino and a pH sensor, the pH of the material was tested within Barcelona sea water. The serial monitor readings in Arduino shown below read that the pH of the distilled water started at 5.91, while seawater was initially pH 7.53. The pH of the seawater rose to 7.62 after terracotta clay was submerged into it. Unfortunately the clay and oyster shell composite altered the pH of the seawater much more than expected, reaching a maximum pH of 10.83. From this investigation it was concluded that the composite would not be suitable for the marine environment in Pujada Bay however, since the pure terracotta clay test did not alter the seawater pH too much it would be an ideal choice of material.



```
15:21:34.132 -> Voltage: 1.253 V | pH Value: 7.53
15:21:35.452 -> Voltage: 1.257 V | pH Value: 7.58
15:21:36.763 -> Voltage: 1.255 V | pH Value: 7.56
15:21:38.075 -> Voltage: 1.257 V | pH Value: 7.58
15:21:39.388 -> Voltage: 1.257 V | pH Value: 7.58
15:21:40.697 -> Voltage: 1.256 V | pH Value: 7.57
15:21:42.012 -> Voltage: 1.259 V | pH Value: 7.61
15:21:43.325 -> Voltage: 1.259 V | pH Value: 7.61
15:21:44.632 -> Voltage: 1.258 V | pH Value: 7.60
15:21:45.980 -> Voltage: 1.260 V | pH Value: 7.62
15:21:47.289 -> Voltage: 1.261 V | pH Value: 7.64
15:21:48.602 -> Voltage: 1.260 V | pH Value: 7.62
15:21:49.908 -> Voltage: 1.260 V | pH Value: 7.62
15:21:51.219 -> Voltage: 1.260 V | pH Value: 7.62
15:21:52.528 -> Voltage: 1.259 V | pH Value: 7.61
15:21:53.863 -> Voltage: 1.259 V | pH Value: 7.61
15:21:55.167 -> Voltage: 1.258 V | pH Value: 7.60
```

```
15:08:31.204 -> Voltage: 1.137 V | pH Value: 5.91
15:08:32.525 -> Voltage: 1.369 V | pH Value: 9.15
15:08:33.843 -> Voltage: 1.444 V | pH Value: 10.19
15:08:35.165 -> Voltage: 1.467 V | pH Value: 10.52
15:08:36.482 -> Voltage: 1.479 V | pH Value: 10.69
15:08:37.797 -> Voltage: 1.485 V | pH Value: 10.77
15:08:39.119 -> Voltage: 1.489 V | pH Value: 10.83
15:08:40.406 -> Voltage: 1.481 V | pH Value: 10.71
15:08:41.746 -> Voltage: 1.469 V | pH Value: 10.54
15:08:43.064 -> Voltage: 1.470 V | pH Value: 10.55
15:08:44.360 -> Voltage: 1.467 V | pH Value: 10.52
15:08:45.676 -> Voltage: 1.469 V | pH Value: 10.54
15:08:46.991 -> Voltage: 1.476 V | pH Value: 10.65
15:08:48.332 -> Voltage: 1.478 V | pH Value: 10.67
15:08:49.643 -> Voltage: 1.479 V | pH Value: 10.68
15:08:50.953 -> Voltage: 1.477 V | pH Value: 10.66
```

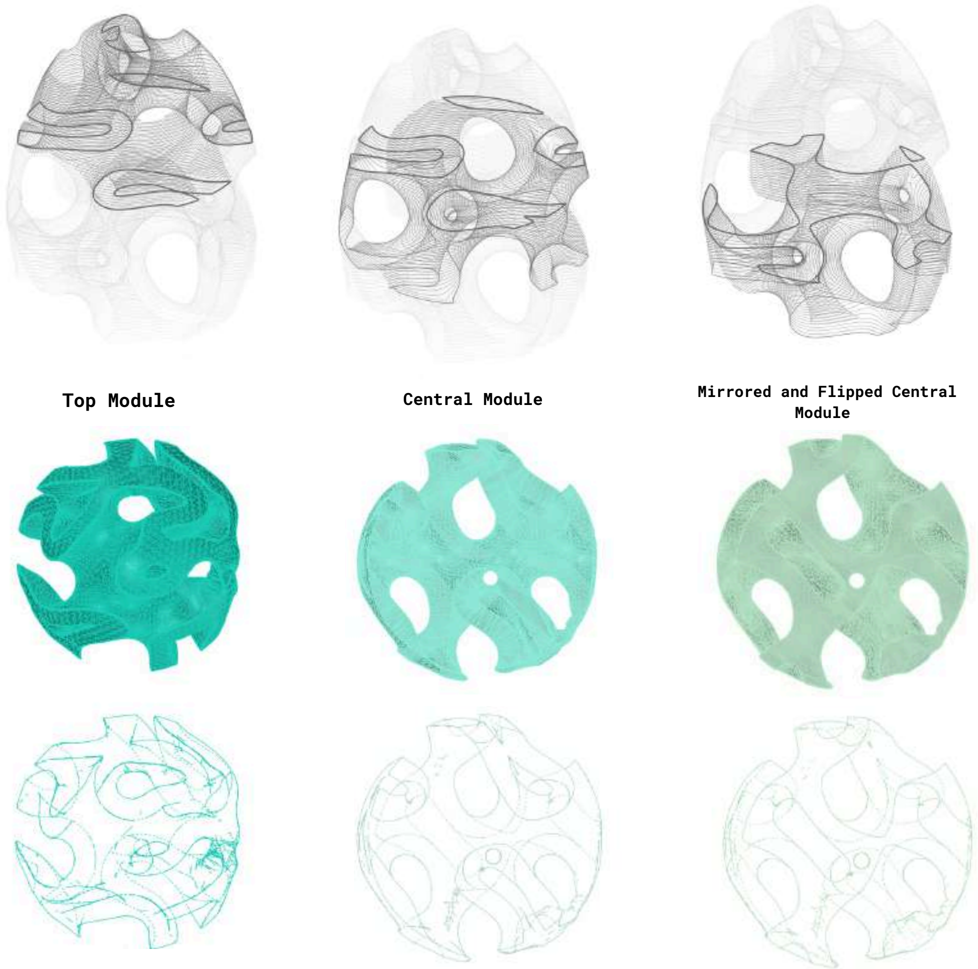

Arduino Serial Monitor Readings

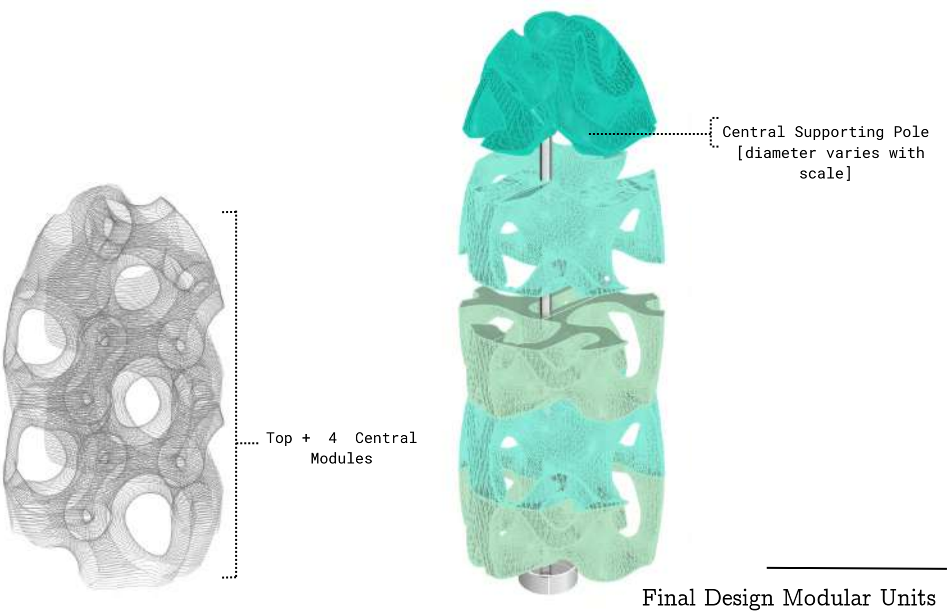

ABB

07 | FINAL DESIGN

Overview

To achieve modularity, a hole had to be removed in each piece for the central support rod to be inserted through. To do this a mesh cylinder was subtracted from the gyroid through the points that were thought to work best. The placement is shown in the diagram below.





Final Design Modular Units

Paste Printer Test

7% Water Content Clay Prototype

Robot Printing

Using the ABB robotic printer at IAAC with an 8mm nozzle, the final geometry was printed at 50 % scale. Each module printed ~2.5kg clay in 20 minutes.

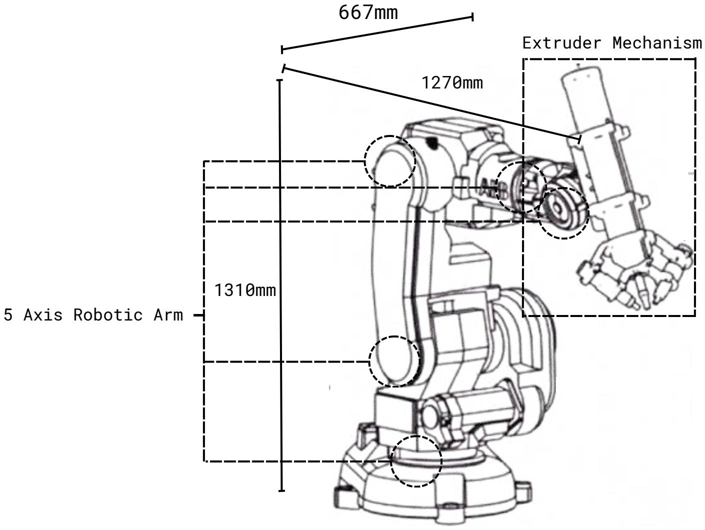


ABB Robotic Arm

Robot Printing


Editorial Shoot

08 | CONCLUSIONS

Conclusions

The final large scale prototype was structurally sound, and satisfied all the aims set out at the beginning of this research. The geometry is complex, providing a suitable habitat for marine life found in Pujada Bay, Philippines. This geometry contains a variety of channels, overhangs and a large surface area that promote marine biodiversity. At the time of writing this, there is still some work to be done before the structure can be tested out in location.

It was a shame that the oyster shell and clay composite failed to work, although predictions would have suggested otherwise. Designing an artificial coral reef out of calcium carbonate still remains a future goal.

Feedback from the final presentation suggested to develop a more efficient joining mechanism to prevent rotation of each module underwater. Such a mechanism could involve a female and male joint that locked in place when the modules were stacked on top of each other. With the layout of the geometry and the orientation in which the modules had to be printed though, this mechanism may have not been successful which is why the central supporting pole was chosen. However, it would be interested to test this idea.

Future developments of TerrAqua involve developing an initiative that promotes Biodesign to local communities most affected by climate change, specifically empowering women to learn advanced technological design methods with 3D printing and biofabrication. The hope is to enrich them with knowledge on how to protect their local ecosystems and allow them to develop an advanced craft trade focused on sustainability.






References

[1] Levy, N., Berman, O., Yuval, M., Loya, Y., Treibitz, T., Tarazi, E., & Levy, O. (2022). Emerging 3D technologies for future reformation of coral reefs: Enhancing biodiversity using biomimetic structures based on designs by nature. Science of The Total Environment, 830, 154749. https://doi.org/10.1016/j.scitotenv.2022.154749

[2] United Nations Environment Programme. (2024, March 6). The world's corals are bleaching – here's why and what it means for the ocean's future. United Nations Environment Programme. https://www.unep.org/news-and-stories/story/worlds-corals-are-bleaching-heres-why-and-what-it-means-oceans-future

[3] Moberg, F., & Folke, C. (1999). Coral reef ecosystem services in the Anthropocene. Ecosystems, 2(1), 18–26. https://www.researchgate.net/publication/331866139_Coral_reef_ecosystem_services_in_the_Anthropocene

[4] Johnson, Z. I., Browning, T. J., Key, R. M., & Barbero, L. (2017). Ocean acidification (Chapter 13). In Climate Science Special Report: Fourth National Climate Assessment, Volume I (pp. 364–392). U.S. Global Change Research Program. https://science2017.globalchange.gov/downloads/CSSR_Ch13_Ocean_Acidification.pdf

[5] Jones, N. (2020, August 11). The eco-friendly alternatives to ocean concrete. BBC Future. https://www.bbc.com/future/article/20200811-the-eco-friendly-alternatives-to-ocean-concrete

[6] (2024, July 10). Reef revolution: How implementation of 3D printing can promote sustainable coral restoration.Manchester Institute of Innovation Research Blog. https://blogs.manchester.ac.uk/mioir/2024/07/10/reef-revolution-how-implementation-of-3d-printing-can-promote-sustainable-coral-restoration/

[7] Pérez-Pagán, B. S., & Mercado-Molina, A. E. (2018). Evaluation of the effectiveness of 3D-printed corals to attract coral reef fish at Tamarindo Reef, Culebra, Puerto Rico. Conservation Evidence, 15, 43–47. https://www.conservationevidence.com/reference/pdf/6858

[8] RRReefs. (n.d.). Pujada Bay, Philippines – Coral restoration project. Retrieved April 3, 2025, from https://www.rrreefs.com/projects/pujada-bay-ph/

[9] Weisstein, E. W. (n.d.). Gyroid. Wolfram MathWorld. Retrieved April 3, 2025, from https://mathworld.wolfram.com/Gyroid.html

[10] Oplusi. (n.d.). Hanging fish house. Retrieved April 3, 2025, from https://www.oplusi.com/hanging-fish-house

[11] Vail Baumer. (2024). Comparing ceramic Fischer-Koch-S and gyroid TPMS scaffolds for potential in bone tissue engineering. Bioengineering and Biotechnology, 12, Article 1410837. https://doi.org/10.3389/fbioe.2024.1410837

[12] DaveMakesStuff. (n.d.). Fischer Koch C(Y) Egg. Thangs. Retrieved April 3, 2025, from https://thangs.com/designer/DaveMakesStuff/3d-model/Fischer%20Koch%20C%28Y%29%20Egg-60714

[13] Thingiverse. (n.d.). Fischer Koch C(Y) Egg. Thingiverse. Retrieved April 3, 2025, from https://www.thingiverse.com/thing:4838412

[14] Pinterest. (n.d.). Pinterest. Retrieved April 3, 2025, from https://uk.pinterest.com/pin/404549979046241005/

[15] Pinterest. (n.d.). Pinterest. Retrieved April 3, 2025, from https://uk.pinterest.com/pin/404549979046241006/

[16] Van Der Weide, C. (n.d.). Eigen werk. Céciel van der Weide. Retrieved April 3, 2025, from https://www.cecielvanderweide.nl/eigen-werk/

[17] Designboom. (2024, June 18). Bartlett student's 3D-printed ceramic cooling solutions inspired by termite mounds. Designboom. https://www.designboom.com/architecture/bartlett-student-termite-mounds-3d-printed-ceramic-cooling-solutions-06-18-2024/

[18] Pinterest. (n.d.) Pinterest. Retrieved April 3, 2025, from https://uk.pinterest.com/pin/404549979046176162/

[19] Pinterest. (n.d.). Pinterest. Retrieved April 3, 2025, from https://uk.pinterest.com/pin/404549979046176531/

[20] Zhang, C. (n.d.). Minimal surface. Catherine Zhang. Retrieved April 3, 2025, from http://catherinezhang.squarespace.com/minimal-surface/?epik=dj0yJnU9S0VWM212T0hsX1FRdWVTeUgwZl9QU1dPdWJmdmhMaFImcD0wJm49Z0J3NElkTWNRdHBqSWxza2ZQd3pSQSZ0PUFBQUFBR2VKZ0hv

[21] YouTube. (2024, April 3). [Title of the video] [Video]. YouTube. https://www.youtube.com/watch?v=1LFLjqf9I8w

[22] Bandana Pottery. (n.d.). Materials. Bandana Pottery. Retrieved April 3, 2025, from https://bandanapottery.com/materials

[22] Ellementry. (n.d.). Why terracotta is such an eco-friendly material. Ellementry. Retrieved April 3, 2025, from https://www.ellementry.com/blogs/news/why-terracotta-is-such-an-eco-friendly-material?srsltid=AfmBOooemDzIZkD6H3oYLUK9D1FMVvRU1-ZLVua6VGNY_nv8n6EOGe5m

[23] Science Focus. (2024, April 3). 3D-printed terracotta coral reefs could save the rainforests of the sea. Science Focus. https://www.sciencefocus.com/news/3d-printed-terracotta-coral-reefs-could-save-the-rainforests-of-the-sea

[24] RRReefs. (n.d.). RRReefs. Retrieved April 3, 2025, from https://www.rrreefs.com

[25] (2024). Title of the article. ACM Digital Library. https://doi.org/10.1145/3656156.3665431

[26] Everplast. (n.d.). 3D marine eco bricks. Everplast. Retrieved April 3, 2025, from https://www.everplast.com.tw/3d-marine-eco-bricks/

[27] Lin, T.-M., & Chen, S.-H. (2024). Marine waste management of oyster shell waste as reinforcement for 3D-printed materials. Elsevier. Retrieved April 3, 2025, from https://ntut.elsevierpure.com/en/publications/marine-waste-management-of-oyster-shell-waste-as-reinforcement-fo

[28] CNT Factory. (2023, December 12). 3D printed oyster shell. CNT Factory. Retrieved April 3, 2025, from https://www.cntfactory.com/2023/12/12/3d-printed-oyster-shell/

[29] YouTube. (2024, April 3). [Title of the video] [Video]. YouTube. https://www.youtube.com/watch?v=HRCgsvpVvZA