Surface pattern for biodiversity enhancement

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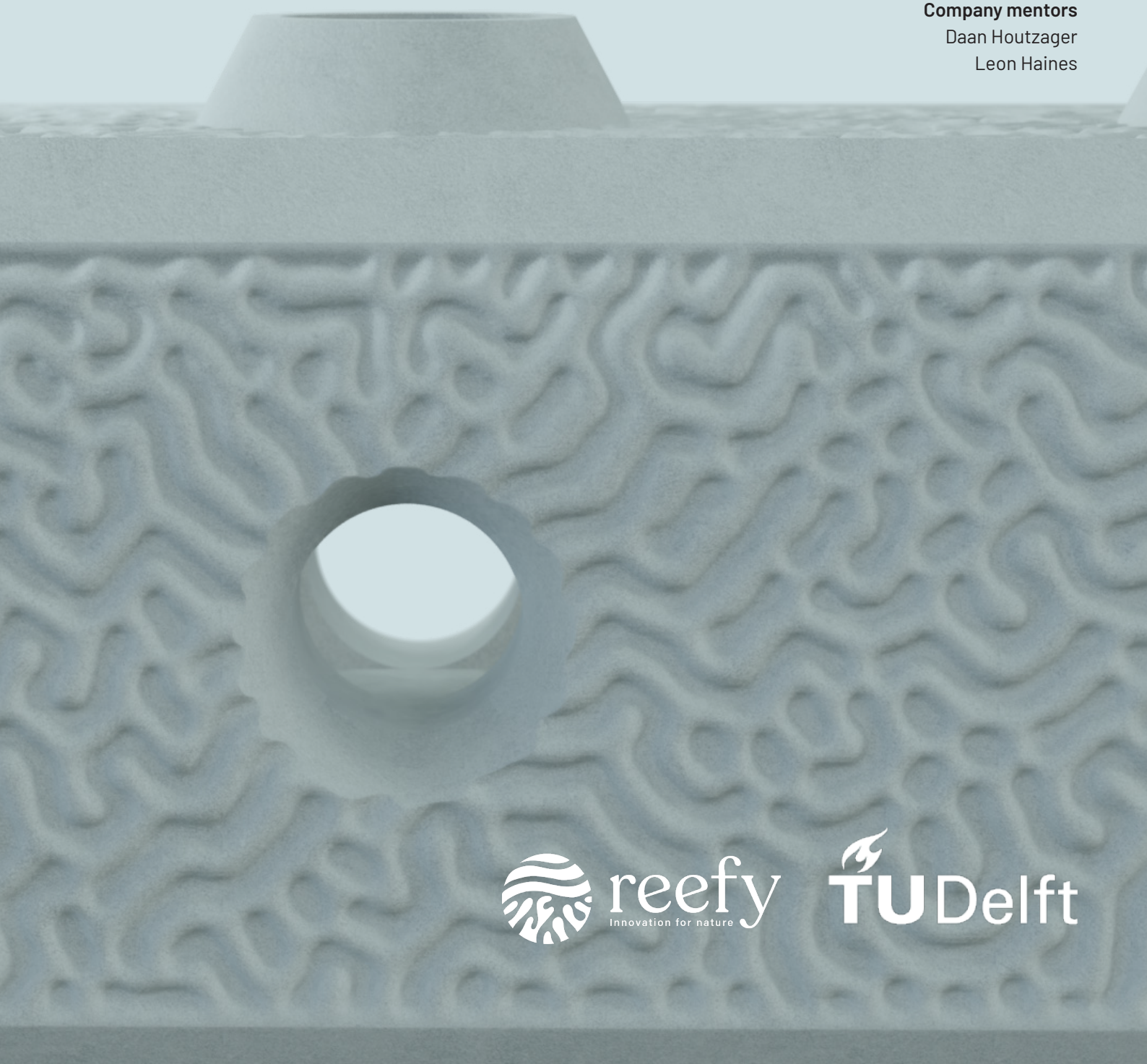


Summary

This graduation report describes the design process towards a three-dimensional surface pattern design that can increase biodiversity and ecosystem productivity on artificial reef structures, like the ReefBlock by the company Reefy (Figure a).

Based on marine life around hard substrate reefs, three important 'reef inhabitants' were identified based on their trophic connectivity in any reef ecosystem (Figure b). A balance between them, creates healthy reef ecosystems.

Therefore, the pattern design must account for all three inhabitants, and based on a literature review, a 'spatial planning' on the surface area of the ReefBlock was identified (Figure a) in the form of specific design features at both structure (centimeter) and texture (millimeter) levels.

The design vision for the proposed pattern design was based on *lobed brain corals*. These versatile natural patterns can create the different design features needed and can be generated using a 'reaction-diffusion' toolset in image editing software.

Using this generative art tool, with specific post-processing steps to meet all requirements, as input for a parametric design tool allowed me to develop a powerful toolset that helped me in my design process and ensured that each design meets the production requirements.

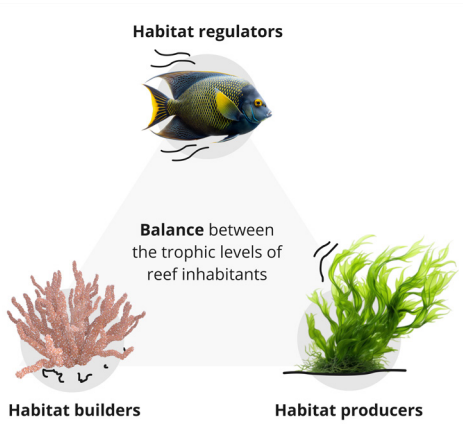


Figure b: The identified reef inhabitants based on trophic connectivity.

A survey on the general aesthetics was conducted to select the final proposed design. And in order to get an idea of the validation of the proposed design within the timeframe of this project, lab tests with microalgae were conducted using small samples of the pattern design. The test results showed great potential for biodiversity enhancement for future field tests (Figure c). Lastly, in order to help Reefy one step in the direction of those field tests, a form liner was produced that can cast concrete tiles (Figure d).



Figure c: Sample from the microalgae test after six weeks of submersion.

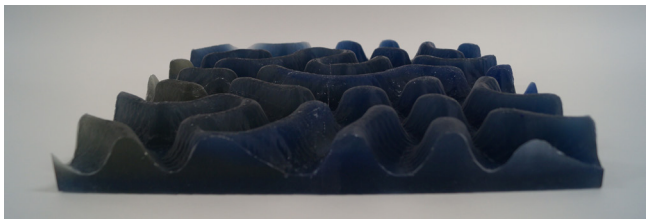


Figure d: Rubber form liner that can cast concrete tiles with the pattern design.

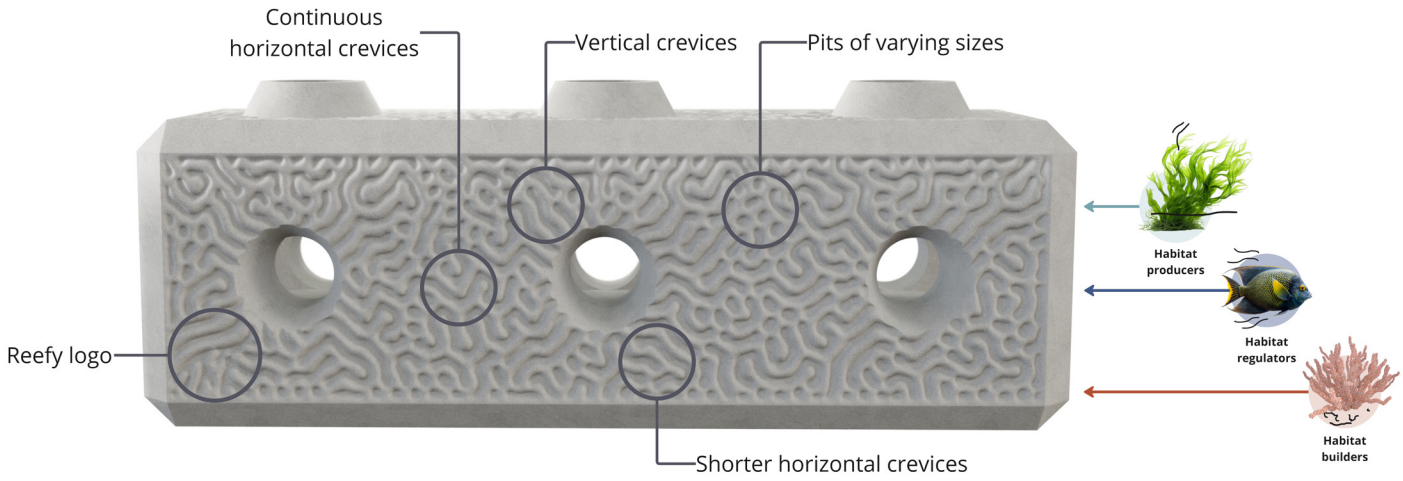


Figure a: The ReefBlock with the proposed final pattern design, and indicating the general ecological design features and branding integration.

Abstract

Reefs are the most important marine ecosystems that support the majority of marine life in our oceans for both temporary and permanent shelter, refuge and food supply. However, reef ecosystems around the world are disappearing and artificial reef structures are an opportunity to help restore them.

This project contributed to the field of artificial reefs, by designing a surface pattern on both millimeter and centimeter scale, that aims to enhance and support biodiversity on the large concrete "ReefBlocks", by the company Reefy. That serve as both artificial reefs and as functional infrastructure, such as breakwaters and dams.

In an extensive literature research, information on marine environments was collected and three main types of inhabitants that can be found in reef communities were identified, including only those that interact with hard substrates like the ReefBlock. The three different inhabitant types were distinguished based on their unique role within ecosystems, which they need to grow, stay balanced and provide the necessary ecosystem functions.

To understand the ecological requirements for the pattern design, existing knowledge on increasing biodiversity with artificial reef substrates was researched and summarized in a micro marine spatial plan on the scale of an entire ReefBlock. The addition of crevices and pits of varying sizes on centimeter-scale and grooves on millimeter-scale were concluded as the main crucial design features that need to be reflected by the final pattern design.

A design vision to aim for biomimicry of lobed brain corals was formulated for the aesthetics of the proposed pattern design. As brain coral patterns have a visually organic complexity and flexibility that allows for the natural implementation of the identified crucial design features. In order to achieve the pattern design vision that meets all the collected ecological, stakeholder and production requirements, a design toolset was developed that combines the power of generative art with the power of parametric design.

The generative art tool allows the semi-automatic creation of lobed brain coral patterns in a similar process to how actual brain corals, and many other examples in nature, receive their pattern from, in a so-called reaction-diffusion system.

With the generative art tool, a black and white 2D image is generated, which is then used as the input variable for the parametric tool. Which directly translates the 2D image into a perfect 3D surface pattern. This method ensures that the pattern design always meets the various production requirements.

In order to support the choice for the aesthetically best-rated design by the general public, a survey with 60 respondents was conducted with questions based on the stakeholder requirements.

In order to validate the effectiveness of the pattern design within the timeframe of this project, a six weeks lab test was conducted using concrete prototypes of the pattern design and microalgae. The test showed promising results for meeting the defined ecological requirements.

Lastly, a rubber form liner was produced in order to help Reefy along with future field tests with the proposed pattern design, in order to validate the conclusions and insights gained in this graduation project, and in real marine environments, for a much longer period of time.

The design toolset was initially created to support the iterative design process and helped to quickly try, test and compare a multitude of designs. But in the end, this toolset has proven to be very valuable for future use by Reefy as they plan on extending their product line with smaller-scale wall panels and for potential adjustments to the proposed pattern design based on their field tests.

Content

Summary
Abstract 2
Content 3
1 Introduction 4
1.1 | The most important marine ecosystems: reefs 5
1.2 | The problem 10
1.3 | The opportunity 10
1.4 | The assignment: Design a pattern for artificial reefs 11
2 Context analysis 14
2.1 | Marine life 15
2.2 | ReefBlocks 19
2.3 | Stakeholders 22
3 Literature review 23
3.1 | Existing solutions 24
3.2 | Meso and micro marine spatial planning 31
3.3 | Overview of most important requirements 33
4 Design vision 34
4.1 | Initial exploration 35
4.2 | Brain coral inspiration 39
5 Design toolset 40
5.1 | Approach to development 41
5.2 | Generative art 41
5.3 | Parametric design 44
6 Concepts 45
6.1 | Work flow 46
6.2 | Surface structure on centimeter-scale 46
6.3 | Surface texture on millimeter-scale 49
6.4 | Pattern design concepts 50
7 Proposed pattern 53
7.1 | Design features 54
7.2 | Expected reef formation 56
7.3 | Microalgae testing 58
7.4 | Form liner for future testing 64
7.5 | Conclusions 67
8 Discussion 69
8.1 | Future implementation 70
8.2 | Recommendations 71
8.3 | Limitations 72
8.4 | Ethics 73
9 Project Journey 74
9.1 | Working towards my learning goals 75
9.2 | Working to the project goal 76
References 77
Appendices 84

1 Introduction

This graduation report describes my design process towards a surface pattern design that can increase biodiversity and ecosystem productivity around artificial reef structures.

Reefs (like coral reefs, in Figure 1) are known to be one of the most important ecosystems in our oceans rising from the seabed, creating a home for the majority of marine life. Right behind and in between reefs the water is calmer, also allowing other types of reefs to develop. And together, these ecosystems are vital for sustaining marine life. Aside from their important function as habitat for marine life, large reefs also play an important role in reducing wave energy, protecting our coastlines.

Figure 1: *Exemplary coral reef (DuikeninBeeld, 2021)*



1.1 | The most important marine ecosystems: reefs

First, some general background knowledge on marine ecosystems and the aquatic environments they occur in is introduced, including terms and concepts that are important to understand, in order to understand the added value of this graduation project in a global context.

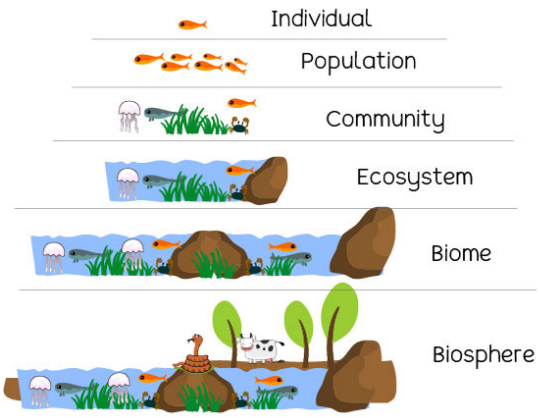


Figure 2: *The different levels of organization in ecology (Levels of Organization in an Ecosystem – Eschooltoday, n.d.)*

Generally, within our **biosphere** we have aquatic (in water) and terrestrial (on land) biomes (Figure 2). A **biome** describes a large area with a similar climate, and determines the type of flora and fauna that can be found in that area (*Levels of Organization in an Ecosystem* – Eschooltoday, n.d.). Biomes contain sets of multiple **ecosystems** that generally share similar 'abiotic conditions'. An **abiotic condition** is a non-living factor of an ecosystem that determines the environmental stressors, like the temperature or water flow (*Abiotic Factors*, n.d.). Within each ecosystem specific **populations** of flora and fauna species form unique **communities** that interact with each other and their environment, adapted to their specific ecosystem (FuseSchool - Global Education, 2016).

1.1.1 | Reef formation

A natural reef is defined as "a ridge of natural (f.e. rock) or biological (f.e. dead or living coral) material rising from the ocean floor towards the ocean's surface." (What Is Computational Design?, 2022).

So, natural reefs can be either "geogenic", non-living, or "biogenic", (once) living, of nature (Figure 3). **Geogenic** reefs provide natural hard surfaces, or so-called substrates, on which certain reef building species can attach to and grow (O'Sullivan et al., 2020). Whereas **biogenic** reefs provide biological hard substrates formed by the growth of the reef building species, on or in between which other marine organisms can settle or live (Dipper, 2022). In other words, reefs that are formed by an accumulation of living on top of (once) living organisms, over successive generations (*Publications | National Parks & Wildlife Service*, n.d.). This behavior actively changes and expands a reef over time, which is why such species are often referred to as reef or habitat builders (Principe et al., 2021). The most important difference is that living organisms (both flora and fauna) grow, take in nutrients, reproduce, and finally, die. It is precisely those 'activities' together that are incredibly important ecosystem functions that support many other living organisms in the harsh conditions of aquatic environments (Libretexts, 2023b).

Each biogenic reef has in common that they started with a few species that were able to settle and live on a substrate that was barren or empty before their arrival (Coral Reef Alliance, n.d.). These so-called **pioneering species** pave the way for next generations of species to settle (Peter Paalvast interview). Increasing the available surface area of a slowly emerging reef, by growing larger over time. Their expansion inherently creates more attachment points for other marine life from the same or different species to settle in between and





Figure 3: *a) Geogenic reef example ("Een Zeepok Is Een Stuk Minder Standvastig Dan Je Zou Denken," 2022) and b) Biogenic reef example (Koraalsoorten Ontdekt Die Bestand Zijn Tegen Extreme Klimaatomstandigheden, 2019)*

help further expand the reef. However, not only more **reef-building species** are attracted by the emerging reef. The accumulation of reef-building species can create complex, three-dimensional structures over time that create many (**micro**) **habitats** of varying sizes and shapes, which other marine life likes to make use of. And, their presence attracts predators around the reef. No matter how small reefs may be at a given point in time, they create incredibly important habitat for other marine life.

Any given surface that is submerged in an aquatic environment will inevitably be covered in living organisms over time in one form or another, if given the right conditions (Hayek et al., 2022; Flemming, 2002). However, not only reefs are covered by marine life, also moving organisms and objects become covered in marine organisms, like whales, moving ships and even the plastic soup in our oceans (Erramilli and Genzer, 2019). Therefore, the availability of geogenic reefs facilitates the existence of such incredibly important biogenic reefs, if given the right conditions.

The phenomenon that there is a collaboration between two or more species which provides benefit to at least one of them, is called a **symbiotic relationship** (Scott, 2023).

1.1.2 | Reefs around the world: types of reefs

Coral reefs are often the first type of reef that come to mind: coral species come in many forms and exist at different depths of the ocean. And it can take over hundreds of years before coral reefs form large, magnificent and highly biodiverse marine ecosystems (Mischa, 2017).

The best known example is of course the Great Barrier Reef near the coast of Australia (Figure 3a), which is actually the largest collection of coral reefs in the world, with 3000 reefs in proximity of each other, making it the largest connected living structure on Earth, that is even visible from space (*What Is the Largest Living Structure on Earth?*, n.d.).

However, corals are not the only type of marine species that build reefs. Other types of biogenic reefs are made by bivalves, such as oyster or mussel beds (Figure 3b), by sand worms, called Sabellaria reefs (Figure 3c), by glass sponges, called marine sponge reefs (Figure 3d), and even by large seaweeds, such as Giant Kelp forests (Figure 3e). These types of organisms have in common that they need a **hard substrate** to attach themselves to, and for them to stay in place on a steady foundation that will not move by the water's movement (Figure 5).



Source: Netflix documentary "Puff: Wonders of the reef" [00:29:00-00:29:40]

Fun fact: There are some recorded cases of corals attaching themselves to broken off pieces of dead coral and actually utilizing the fact that these pieces are moved by the waves, as a sort of mobile lifestyle (Leon, Reefy). Corals called 'Walking Dendros' even established a symbiotic relationship with small worms that gain protection inside the coral and use it as a sort of 'coral caravan' when moving around. In return they keep the coral upright to prevent them from being buried in the sand and to maintain access to sunlight and nutrients.

Figure 5: *The exception: mobile lifestyle of sessile species (Watch Puff: Wonders of the Reef | Netflix Official Site, n.d.).*

Not all existing marine coastal ecosystems require a hard substrate to start forming. Some grow on 'soft'

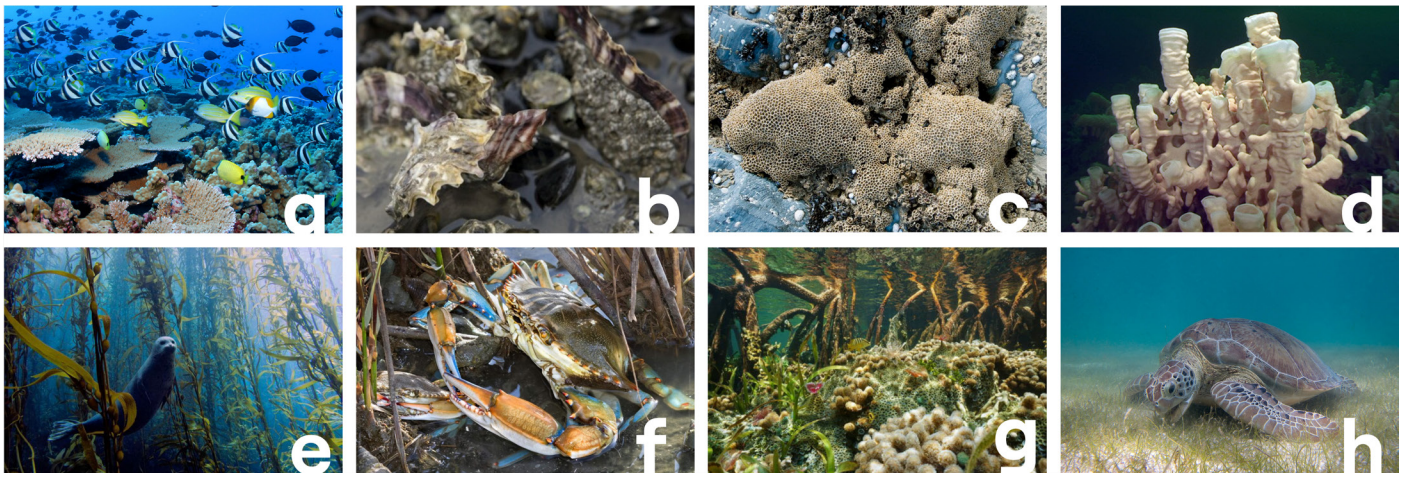


Figure 4: ***a) Coral reef*** *(EU Reporter, 2021). b) Oyster bed (DPG Media Privacy Gate, n.d.).* ***c) Honeycomb sand worm (Sabellaria) reef*** *(Honeycomb Worm Colony by Science Photo Library, n.d.).* ***d) Deep sea Glass sponge reef*** *(Fullscreen Page | Sea Dragon Charters, n.d.).* ***e) Giant Kelp forest*** *(Harbor Seal in a Kelp Forest, 2023).* ***f) Salt marsh*** *(Limited, n.d.).* ***g) Mangrove forest*** *(Seadam, n.d.). h) Seagrass meadow (Netherlands, 2022).*

sediment, like sand or mud. Examples of such ecosystems are so-called salt marshes (Figure 3f), mangrove forests (Figure 3g) and seagrass meadows (Figure 3h). These types of organisms need a **soft substrate** to root themselves in, to hold themselves in place. However, these ecosystems are out of scope for this project, as the ReefBlock creates a hard substrate reef.

1.1.3 | Aquatic environments

The oceanic water body can be divided in different zones (Figure 5). Sunlight availability decreases rapidly with depth, and generally it can penetrate the water column up to 200m, referred to as the **photic** (or sunlight) zone. Beyond the photic zone little to no sunlight is available, and is therefore called the aphotic zone (Bailey, 2019). The majority of the oceanic water body is in the **aphotic** zone, which is mainly open ocean with depths generally up to 4000m. Only few places of the ocean go deeper than that, with the Mariana Trench as the deepest point up to 10.000m, in the so-called **abyssal** zone (Libretexts, 2023b). Despite there being little to no light available and temperatures down there are really low, biogenic reefs do exist on the deep ocean floors (see FigureXd). However, both the aphotic and abyssal zones are out of scope for this project, because these are not target locations for ReefBlocks.

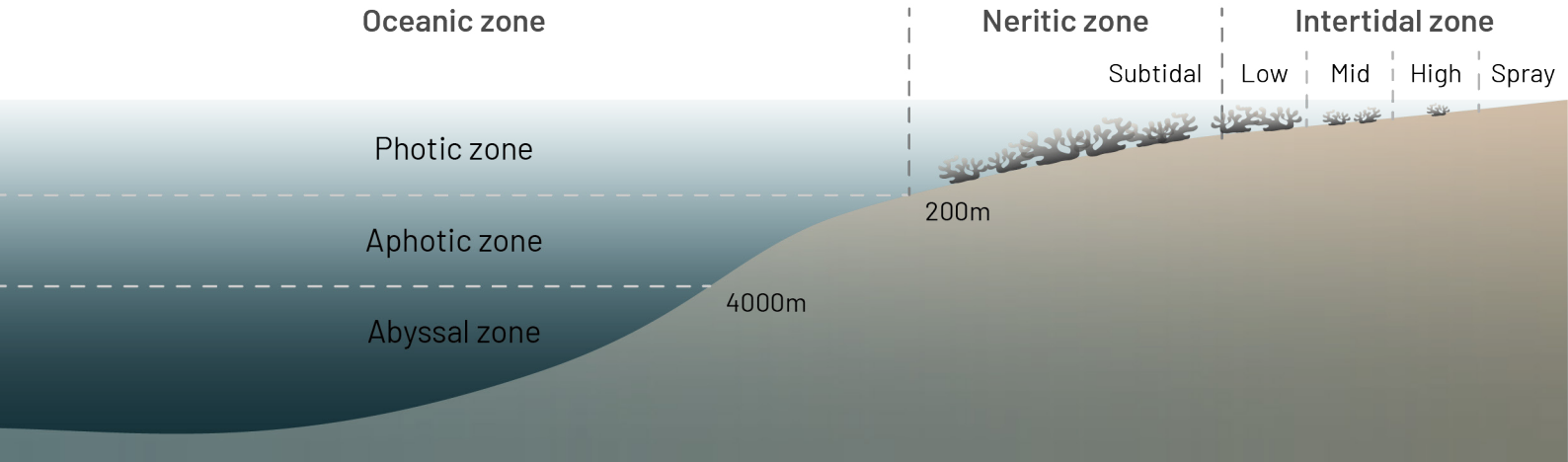
The water closest to land is called the **intertidal zone** (Bailey, 2019). The depth of this water fluctuates during the day, referred to as **tidal fluctuations** that create currents (*What Is the Intertidal Zone?*, n.d.). These cause alternating periods of flood and periods of drought higher up the shore, meaning that some zones are part of the day below and part of the day above the water level. The intertidal zone is therefore further divided into four sub-zones. The **spray zone** is always above the water line but is kept moist due to water spraying upward from the wave impact on the shore. Below that the shore is divided into the **high tide**, to the **middle tide**, to the **low tide zone**, which are exposed to air the longest to the shortest, respectively (*What Is the Intertidal Zone?*, n.d.).

Transitioning from below to above the water level is a drastic change in living conditions, and one that not all marine life is able to survive (Fisheries, n.d.). The organisms that are able to live both below and above water are still exposed to extreme conditions. The height of the ecosystem above the (average) water level determines the length of the period it is exposed to air, direct sunlight (and with that, rising temperatures), as well as wave exposure (with low to high dynamics). These factors have a large influence on which species are able to survive and remain settled in the intertidal ecosystems (Little et al., 2009).

Below the lowest low tide, we enter the **subtidal zone**, in the so-called **Neritic**. This zone is below the water level at all times and is also completely within the photic zone. Which means that, in these relatively shallow waters, ecosystems have plenty of light and oxygen available and the waters are relatively warm, supporting many photosynthetic organisms. In different geographical locations and depths, very different marine life can be found. However, what they all have in common is that most of (the known) marine organisms live in the Neritic zone (Bailey, 2019).

What all of those coastal ecosystems have in common is that they are a foundation for marine habitats, yet in turn they are dependent on many **symbiotic relationships** that each play an important role in keeping the reef healthy to continue growing.

Figure 6: *Divisions of the oceanic water body.*



1.1.4 | Why reefs are important: roles of reefs

Reefs are home to many marine species



Figure 7: *Coral reef with many marine species (EU Reporter, 2021).*

Reefs are static structures protruding from the seabed that will gradually form a rich accumulation of marine life in a confined area, as they will be inevitably encountered by many different marine organisms present in the water column. Therefore, reefs will always have relatively high species abundance. The increasing presence of marine life on the reef not only enhances its biodiversity, but also attracts more of the same and other species (Figure 7).

While some organisms, such as reef-building species, attach themselves permanently to the reef structure, other types of organisms will interact with the reef only temporarily.

Corals are one of the most diverse types of reef building species that provide a wide variety of ecological functions. That is why coral reefs alone provide a habitat for 25% of all marine life, while they cover merely 1% of the earth's surface (Hoegh-Guldberg et al., 2019). Therefore, the functions of reefs can be best understood by looking at the morphologies of corals and conclude their physical functionality (Cresswell et al., 2020):

- Providing a substrate for other organisms to attach to and increasing available surface area.
- Offering hiding spots and refuge pathways for small organisms by creating a wide variety of microhabitats in between the complex three-dimensional structures.
- Providing overhanging ledges that create shaded and sheltered areas.

Reefs are hotspots for food



Figure 8: *Large fish assemblies above a coral reef (Paul, 2023).*

As visible in Figure 3, healthy reefs are a home to many more species than the pioneering reef building species themselves and form absolute hot spots for marine life. The presence of reefs increases the abundance of fish assemblages in the whole coastal area, as biodiversity attracts more biodiversity (Medina et al., 2021). And therefore, even provides us humans with a more abundant supply of seafood.

All marine life is part of a food chain divided into four so-called **trophic levels** (Figure 9) which is defined by what their food source is and who they are in turn eaten by (Evans et al., 2021; Libretexts, 2021).

Each species that settles in or around the reef plays their own role within these trophic levels, and will attract the presence of organisms with either similar or

Figure 9: *Marine trophic levels.*

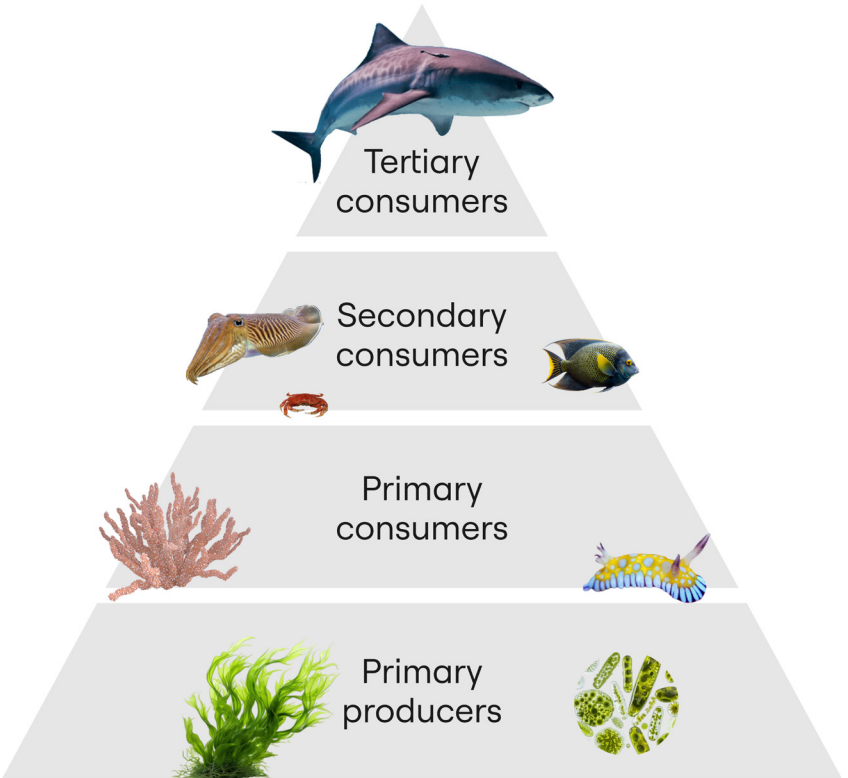




Figure 10: *A coral reef at the 'feet' of a mangrove forest (Roast, 2024).*

different roles in the food chain. The complex structure of the reef allows species of lower trophic levels to hide and refuge in pathways. Over time, as the reef expands in species richness (the amount of different species) and abundance (the amount of individuals per species), it becomes a hotspot for food. For both marine life that live in proximity to the reef and to us humans.

- Providing a wide variety of marine life that are all part of different trophic levels.
- Supporting biodiversity through its high species richness and abundance.



Figure 11: *A seagrass meadow in a lee area, with visible algae growing on top of the seagrass leaves (Boness & Boness, 2012).*

Reefs enhance the surrounding environment

Natural reefs can grow into large structures that function as important **breakwaters**, reducing wave energy before waves reach our shores (Scyphers et al., 2011; Harris et al., 2018). This means that reefs change the environmental stressors, such as water velocity and temperature, with their rigid structure.

Due to shadows created by their structure, they create a larger available range of water temperatures (Perkins et al., 2015), which may provide some species with better living conditions.

Due to their breakwater function they may even enable the formation of other types of reefs (Figure 11 & Figure 10). Right behind and in between large reefs the water is calmer, creating so-called 'lee' areas, allowing for example seagrass meadows to develop that otherwise would not have (Guerra-Vargas et al., 2020).

Multiple reefs in proximity together influence the environment, and with that, each other. Each reef is a separate ecosystem, however, their community is influenced by other ecosystems nearby.

Meaning, it is important to understand that there is a connectivity between ecosystems and that even between different types there can be a sort of symbiotic relationship.

- Providing calmer 'lee' areas that can support both marine life and the formation of other marine ecosystems.
- Providing the surrounding environment with a larger range of available temperature.
- Providing surrounding ecosystems with higher biodiversity in the environment.

1.2 | The problem

In the last three decades, our coastal ecosystems such as coral reefs, have been declining at a fast rate due to e.g. climate change and human activities, which are causing reef-building species to die at a faster rate than they are able to grow (Beck and Airoldi, 2007; Marine Life, n.d.).

Climate change causes the mean temperatures of the earth and oceans to rise. Yet not all marine life is able to adapt or move away from the changing living conditions (like reef-building species), and are dying because of it.

Human activities that have caused a decline in reefs involve, for example, overfishing which causes populations of reef-building species, like oysters or mussels, to decrease faster than they can grow (Beck and Airoldi, 2007; "*Restoring Shellfish Reefs*," 2020). And worse, a commonly used industrial method of fishing, called bottom trawling (Figure 12a), involves dragging fishnets over the ocean floor, potentially destroying established reefs (*What Is Bottom Trawling*, n.d.).

Our global economy brings diseases and species from across the globe to be introduced in environments where they do not have natural enemies and can become invasive to native species (Bradford et al., 2020; *Invasive Species*, n.d.). The biggest challenge for reefs is often their slow growth rate that cannot keep up with the disruption of habitat and balance.

Consequently, with the decline of reefs, our coasts are less protected. If wave energy is not reduced by the time the waves reach our coasts, they are larger and hit it with higher impact, speeding up coastal erosion.

Unfortunately, most of the marine infrastructure that we build to counteract erosion of the coastline, comes in the form of reinforcements in the most efficient and cheap way possible. In other words, these structures are large smooth surfaces casted with concrete, that replace the natural (often) rocky shores that were once there. On these smooth surfaces only limited types of marine organisms can attach and survive, and are therefore mainly dominated by fast-growing algae (Bishop at el., 2022) (Figure 12b). Comparing that to rocky shores that support much greater biodiversity due to their structural variability, these smooth marine structures are undesirable from a biodiversity point-of-view.



Figure 12: *Bad human interventions, with* ***a) Bottom trawling*** *(Kane, 2023) and* ***b) Homogeneous marine infrastructures*** *(Hardening Shorelines to Reduce Saltwater Intrusion and Coastal Erosion May Lead to Inland Flooding - NCCOS Coastal Science Website, 2024).*

1.3 | The opportunity



Figure 13: *ReefBlocks in configuration in context (credit: Reefy).*

The company Reefy has created one of the first modular artificial reefs that take on the natural breakwater function of reefs. By means of their "ReefBlock" (Figure 13) they are able to effectively dissipate wave energy for coastal protection, while simultaneously providing a substrate and habitat to support a complex coastal ecosystem.

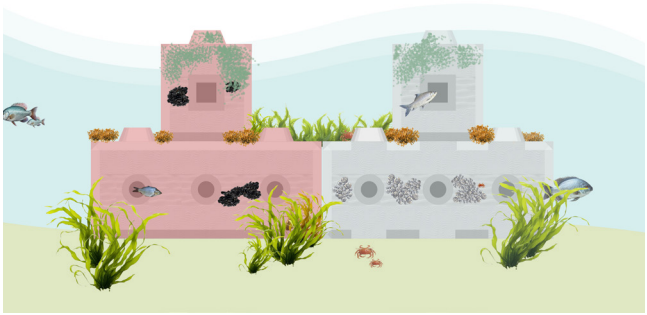


Figure 14: *Structure of the ReefBlock in front and side view, stacked.*

The structure of the ReefBlock (Figure 14) is based on technical requirements for stability and modularity, while providing a home to larger marine animals.

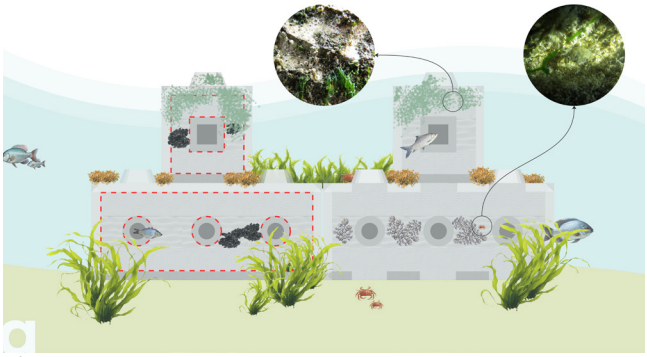


Figure 15: *Available surface area for the pattern design implementation.*

Whereas the surface area (Figure 15) creates the opportunity to provide a foundation for micro and macro organisms, by means of a surface pattern design that can be enhanced for boosting biodiversity.

1.4 | The assignment: Design a pattern for artificial reefs

Because of the symbiotic nature between reefs and marine life, it is vital to attract a variety of local species to maintain an ecosystem. To support that, a structured surface can attract certain species on a small scale by creating different abiotic conditions.

Currently, the ReefBlock has two wave-like textures (Figure 16). Deep surface patterns (2) have been shown by Reefy to double relative diversity, as measured in the Simpson diversity Index (see Chapter 2.2.2), compared to smooth concrete surfaces, on which mostly micro and macroalgae cultivate (Figure 13). This indicated the potential to optimize a custom design for ecology in combination with aesthetics wishes to attract relevant stakeholders, applied to the specific use case of the ReefBlock.



Figure 16: *ReefBlock in reference to the makers and with the two different surface structures, with 1) shallow and 2) deep structures (credit: Reefy).*

Therefore, it is my assignment to:

- Understand ecological requirements that influence the desirability for the marine life target group;
- Understand stakeholder and production requirements that influence the viability and feasibility of the surface pattern;
- Indicate the effectiveness of the created design that should support biodiversity;
- Produce the pattern design in a production form liner.

The effectiveness of the final design cannot be validated in a natural environment within the timeframe of the project. However, the TU Delft has access to microalgae strains, which if grown on the designed surface, can be used as an indicator to test certain abiotic conditions much faster in a controlled environment. Hypotheses were formulated about the predicted development of bio-colonization on the surface texture and the created unique aesthetics of the developing ecosystem on the ReefBlock. For the project brief see Appendix A.

1.4.1 | Assignment

"Support a biodiverse ecosystem on the surface area of an artificial reef block, by designing a production mold formliner that creates a surface texture with a variety of abiotic conditions and a desired aesthetic pattern."

1.4.2 | Approach

In this project I refer to a 'surface pattern design'. However, for this surface pattern I distinguish the surface texture and a surface structure. As I will demonstrate in my research, the pattern must be designed at both millimeter-scale (texture level) and centimeter- scale (structure level). Therefore, I distinguished four levels of the ReefBlock context:

- **Meta level**: the expected impact of the pattern design on the reef community over time
- **Macro level**: the surface pattern design as an ecosystem, providing trophic connectivity
- **Meso level**: the surface structure that provides shelter and refuge opportunities
- **Micro level**: the surface texture that provides settlement opportunities

With this graduation project I aimed to contribute to the research field of marine coastal ecosystems, by researching the needs of marine life at the ecosystem (meta), trophic connectivity (macro), and species (meso & micro) levels. By comparing the needs of different marine life categorizations and drawing inspiration from biomimicry and existing knowledge, I formulated ecological requirements which guided me in the exploration of different designs. By means of biolab tests with microalgae I aimed to indicate the effectiveness of the proposed design pattern and by means of a survey I aimed to collect and understand the general public's opinion regarding the overall achieved aesthetics of the ReefBlock, as this influences its marketability and cultural meaning in a larger context. Lastly, by producing a physical form liner with the final proposed design, a first step towards future field tests with this design was made. Reefy will later use the proposed pattern design for monitoring purposes in an actual marine context, yet out-of-scope for this project, to assess how well it meets all the requirements.

In the future, the pattern design can be used for the ReefBlocks, but it also creates the potential to be used for any other type of concrete structure placed underwater or on existing or new quay walls.

Despite lacking prior knowledge of the marine context and no experience in designing for marine life specifically, I was supported by Reefy's in-house biology expertise. Moreover, Reefy has access to a network of relevant experts and I made use of this to better understand the most important requirements.

This project allowed me to design a novel marine biodiversity enhancement pattern design, with potential global implementation and impact. This potential impact has been a significant motivator for me to take on this challenge.

1.4.3 | Learning goal 1: Learn how to use parametric design

Computer Aided Design (CAD) is powerful software for design projects and enables the creation and simulation of complex three-dimensional surface structures and textures within a digital environment. These tools allow you to view your model in 3D and even analyze it in 4D, providing a dynamic perspective on how the design might behave over time, before even needing to produce a physical prototype. In recent years, computational CAD tools are emerging where the design relies on algorithms and adjustable parameters to solve the design problems (*What Is Computational Design?*, 2022).

Fortunately, many of these computational tools use visual programming instead of text-based code, allowing me to build a parametric model without needing prior coding experience. The result of this parametric model is a visual flowchart that graphically represents each step of the design, allowing for automation and real-time manipulation of complex designs. As the parameters (inputs) are adjusted, the model updates changes accordingly. Allowing designers to quickly explore different iterations of a design, consecutively. This flexibility is powerful when multiple design variables must be tested and optimized, like in this project.

For this project it was one of my learning goals to become familiar with using and taking advantage of such parametric design tools in my design process, and to be able to achieve the complex, 3D structure that is needed for a successful outcome, which is not created as flexible with traditional CAD tools.

1.4.4 | Learning goal 2: Conduct a biolab test with microalgae

The use of a biolab test with microalgae was first introduced when I enlisted my chair for this graduation project, as she is a microbiologist. The microalgae test offered a great method to validate a final pattern design within the timeframe of my graduation project. The plan was to grow one or more microalgae cultures in the weeks before conducting the test and in the meantime building the necessary test setup, that would allow me to submerge a concrete prototype in the tank with a growth medium and microalgae, and to connect a pump to circulate the water. The IDE Biolab, where the tests were conducted, did not have prior experience with such a setup and so we had to come up with a plan from scratch. Therefore, at the start of my project there were a lot of insecurities about how to conduct the test and what to do if the microalgae were not growing on the prototype or, possibly, dying. And so in the test plan I had to make sure that the only variable in the test setup was the geometry of the prototype. That way, it would be more easy to identify which variables can be altered in the test setup in order to improve the microalgae growth and survival if needed. This means that it was necessary for me to test if concrete can be used for the prototype, if the microalgae survive being circulated by a pump, and which microalgae are able to settle on concrete.

Before this graduation project, I had no prior lab experi-

ence, and so had never worked with microalgae before. Which made this an interesting learning goal for me, as this offered the opportunity to become familiar with lab work and to become more experienced in managing and conducting such a test by myself (and with help from supervisors).

1.4.5 | Report structure

Why biodiversity is important and what this means in a marine context, is explained and elaborated in Chapter 2. As well as a breakdown of the entire context of the ReefBlocks of which the pattern design is part of, such as the production and the stakeholders.

Over the years many different initiatives have been explored to attempt to restore or preserve existing natural reefs. As well as the attempt to create new types of man-made reefs, of which many examples are already present on our ocean seabeds: so-called artificial reefs. Exactly why structural variability is beneficial for biodiversity and how exactly these benefits can be exploited and maximized in artificial reefs, is discussed in Chapter 3. The interpretations and requirements from that literature research, on which I based the design decisions for the proposed design, are concluded in Chapters 3.2 and 3.3, respectively.

For the final pattern design I defined a design vision based on brain corals (Chapter 4). To achieve that design vision I developed a design toolset (Chapter 5) that combines the power of generative art (Chapter 5.2) with the power of parametric CAD design (Chapter 5.3).

Based on the existing knowledge and the design vision, concepts were created in an iterative process using the design toolset (Chapter 6). In order to collect some insights into the general public preference of the aesthetics, a short survey was conducted with 60 responses in order to determine the best design direction (Chapter 6.4.1).

And finally, a proposal was made for a pattern design, that brings together the most important aspects to increase biodiversity on the ReefBlocks (Chapter 7).

Within the short period of this graduation a test setup in a marine environment was not feasible, as such monitoring can take up to 2 years, before useful conclusions can be made about the effects on biodiversity. So, in order to evaluate the final design at least to some extent, a small-scale test with microalgae in a lab environment was set up in order to monitor three distinctive samples from the pattern design on a 1:1 scale. See Chapter 7.3 for the experimental setup and outcomes.

As final deliverables for the company, and to validate the feasibility, a sample of the complete design was produced in a form liner of 400x400mm (Chapter 7.4).

Lastly, this report discusses the future implementation of the final pattern design (Chapter 8.1), as well as the recommendations for future research (Chapter 8.2), the limitations of the design and used tools (Chapter 8.3) and the ethics involving this project (Chapter 8.4).

2

Context analysis

To understand all the requirements for the pattern we need to understand the context. This section describes all the stakeholders and their requirements for the reefblocks. From the marine life that will eventually inhabit the reefblocks, to the way that the reefblocks are produced and the way the pattern will be created on to this block.

The most important conclusion in this chapter is that there are three types of reef inhabitants identified that are always present in any type of reef in any biome, and that influence a reef community with a similar role, based on the trophic level it is part of (Figure 17). These classifications are based on existing literature, however the terms used are made up for the purpose of this project and the context of the ReefBlocks.

The three identified reef inhabitants are:

1. **Habitat builders**: sessile species (who are permanently attached) that expand the reef with their own growth
2. **Habitat producers**: sessile species that provide the reef with nutrients
3. **Habitat regulators**: mobile species that control the balance in the reef community

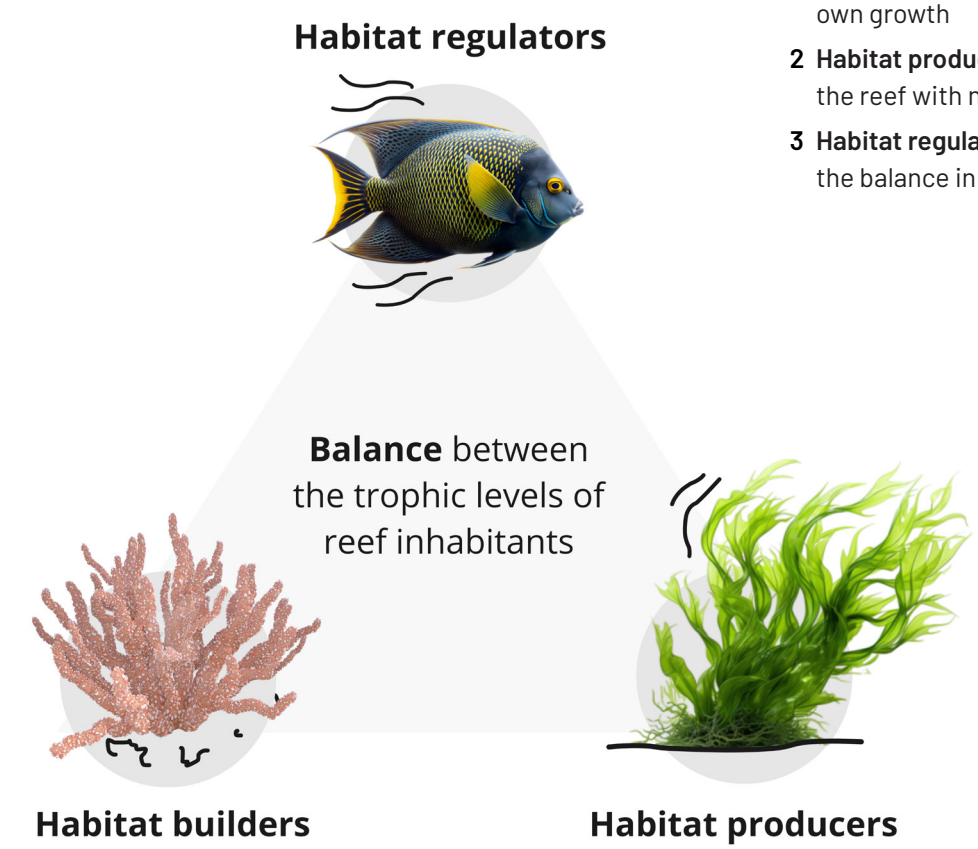


Figure 17: *The identified reef inhabitants: Habitat builders, producers & regulators.*

2.1 | Marine life

A big part of this graduation project is to understand the needs and relationships of marine life in and around reefs. An analysis was done to explore natural reef structures, with regards to the abiotic conditions that are interesting and important to adopt in artificial reef structures.

The main research question that will be answered in this section is: "What marine life should be designed for?" Accompanied by the sub-questions: What are the key influences on reef formation? What are the relevant keystone species?

2.1.1 | Abiotic conditions influence reef formation

As described in the introduction, different types of reefs are distinguished. The type of reefs that can be found depends entirely on the geographical location you are looking at.

The reason why is because several abiotic factors influence the types of organisms that will inhabit each region and are able to survive there (Little et al., 2009). In a marine ecosystem, relevant abiotic factors to my project, include:

- **Water velocity** and turbulence are influenced by the incoming wave energy, in relation to the geographical location and orientation of the surface, and determine which species can settle down on which ecosystem and what surface (Armono et al., 2001). This is especially true for the supply of planktonic organisms, nutrients and oxygen, and the potential accumulation of them in a specific location.
- **Salinity level** and **water temperature** are directly influenced by the geographical location and the depth of the reef. And both these factors dictate which species are present in the ecosystem (Zhu et al., 2024).
- **Light availability** is influenced by the depth of the sea floor, and by the surrounding abiotic and biotic environment potentially creating cast shadows. This abiotic factor determines which species can live where in the ecosystem (Libretexts, 2023b).

2.1.2 | Ecological succession influences the reef community

On the intertidal shores a zonation is clearly visible by observing what marine life is found at specific heights, determined by who can survive in either or both scenarios (always above up to always below water level).

What is important to keep in mind is that in the intertidal zone the reef community can actually vary greatly throughout the year (see Figure 18), depending on the season, depending on the zone the reef is located in and depending on the dynamics of the waves the reef is exposed to. If a reef is exposed to wave impact, the established **bio-colonization** can actually be washed off the shore, partially or entirely, due to wave impact (Little et al., 2009; Paalvast, 2011):

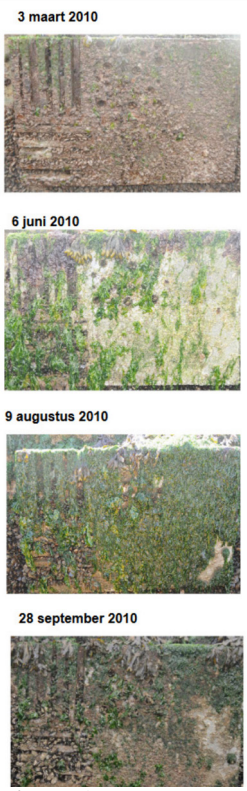


Figure 18: *Ecological succession in the intertidal zone (Paalvast, 2011).*

However, this allows for new, and potentially different, pioneering species to colonize the now exposed substrate. As an ecosystem starts to form and expand, it always undergoes what is called '**ecological succession**'.

"Eventually, if enough time passes, ecosystems will reach a so-called '**climax community**', when no new species are added and no species leave the community. This is when the ecosystem is considered stable" (Libretexts, 2023a).

The constantly changing and extreme conditions in the intertidal zone make it that the established community structure can be washed away or killed partially or entirely, making space for new species to colonize the reef. Which is why ecological succession is faster in these zones than in any other zone (Paalvast, 2011). Reefs in the subtidal zone are less prone to extreme changes in the community structure and a more gradual ecological succession will take place up to the climax community.

2.1.3 | Marine lifestyles influence reef composition

Different marine species can exhibit a variety of lifestyles within the same habitat. These lifestyles are categorized by how organisms move and interact with their environment (Dipper, 2022):



Mobile species, such as fish, crabs, and shrimps, can actively move and change location.



Sessile species, like corals and oysters, are physically attached to a substrate and remain fixed in place.



Planktonic species, like phytoplankton and (coral) larvae, that drift freely in the water column.



Benthic species, such as clams and sea stars and benthic macroalgae grow and live on or in the seafloor.



Epiphytic species, such as certain types of microalgae, grow on the surface of either other organisms, like the fronds of kelp, or of hard substrates, like artificial reefs.

These different lifestyles illustrate the diverse ways marine organisms interact with their environment, contributing to the complexity of a reef community. Reef ecosystems can be seen as micro cities with a diverse range of inhabitants that all play a different role in maintaining the city balanced and growing.

2.1.4 | Ecosystem engineers maintain reefs

Within ecosystems different species can have very different roles in the community. For a large part the community is determined by specific abiotic conditions, such as water velocity, temperature, salinity and light, that are found in specific geographic areas. However, some species have a larger influence on the community structure simply by being part of it, than other species within the same ecosystem. Species whose actions and presence significantly influence community structure, by creating major changes in the ecosystem, are called '**keystone species**'. In fact, it could be argued that all species within an ecosystem can be considered keystone species to some extent, as they all have some form of impact on their environment (Little et al., 2009). However, there is no single species that can be found in all the marine biomes (Libretexts, 2023a), nor does a single species have the same impact in different ecosystems. Meaning that the same species can be a keystone species in one ecosystem and in another they are not particularly (Little et al., 2009).

Whether the impact of keystone species is positive or negative depends on the balance and interaction with the other present species. In the cases where their impact is positive, they are considered essential for maintaining the health and stability of the ecosystem. In literature such keystone species are often referred to as '**ecosystem engineers**' because they create, modify, or maintain habitats for the entire reef community (Alves et al., 2017). They play an important role in shaping the ecosystems they have inhabited, either by directly building habitats or by altering the physical structure of their surroundings. Even more, coastal and marine environments have an abundance of organisms that may be considered ecosystem engineers and are further classified into two groups: 'autogenic' and 'allogenic engineers' (Alves et al., 2017; Rigolet et al., 2014).

- **Autogenic engineers** modify and physically build the environment they live in through the presence and growth of their own physical structures (Alves et al., 2017), which results in the expansion of the reef into a complex three-dimensional structure. Their physical presence provides an ecosystem service to the reef community, by f.e. allowing other organisms to attach to, live between or even, inside them.
- **Allogenic engineers** modify the environment through their activities and behaviors (Alves et al., 2017). By doing so, they provide ecosystem services in the form of consuming, removing or redistributing material in ways that change the physical structure or resources available to other species (Rigolet et al., 2014).

2.1.5 | Roles of ecosystem engineers

Based on the classifications of ecosystem engineers a general marine life overview was created. This overview identifies and distinguishes the important roles that different reef 'inhabitants' can have, based on the trophic levels (Figure 19). And who are all needed to sustain a balanced marine habitat, in any marine biome. These inhabitants only regard relevant marine organisms that interact with hard substrates in the photic zone, and actively settle, shelter, feed or breed in or on a reef similar to ReefBlocks. Important to note is that the inhabitant types in the marine life overview are invented for the purpose of my project, and are not exactly identified the same way in literature.

In the marine life overview, two roles for autogenic engineers and one role for allogenic engineer are distinguished, each with two subtypes (Figure 19):

Autogenic engineers

1 **Habitat builders**: including 'hard' & 'soft' reef builders
2 **Habitat producers**: including 'macro' and 'micro' producers

Allogenic engineers

3 **Habitat regulators**: including 'grazers' and 'predators'

Autogenic engineers

With **habitat builders** I refer to reef-building species, also called '**habitat formers**' (Little et al., 2009), that permanently attach themselves to hard geogenic or biogenic substrates. They are primarily sessile, and create succeeding biogenic layers, creating a growing three-dimensional structure. And by doing so, they add texture and complexity, creating microhabitats for other organisms, simply by their presence and growth (Potet et al., 2021; Howie and Bishop, 2021).

- **Hard reef builders**: habitat builders that form a next biogenic layer of hard substrates that other or the same species of organisms can attach on top of each other and continue to extend the reef over time. Most of these species have calcareous attachment methods that form permanent bonds with the substrate, like corals. These species play a crucial role in reef formation for land protection, for the role of reefs as breakwaters.
- **Soft reef builders**: habitat builders that form a soft biogenic layer that can grow tall or 'branch out', and that grow on top of geogenic or hard biogenic substrates. Because they are soft, they do not provide a biogenic layer that other or similar organisms can attach to. However, they do also provide habitat for refuge or for breeding for specific (mobile) marine species. Like for example the sea anemone and the clown fish.

With **habitat producers** I refer to organisms that also attach to and grow on hard substrates, but they fulfill the additional role of so-called '**primary producers'**. Primary producers are at the bottom of the food web and therefore have a vital role for all trophic levels above it (Evans et al., 2021). They are organisms that produce their own food from the sun, also known as '**autotrophs**', and are eaten by other (herbivorous or omnivorous) organisms (*Food Web*, n.d.).

In the context of ReefBlocks the main relevant types of habitat producers are macro- and microalgae, as they visibly grow on the smooth and illuminated surfaces. The term 'producer' refers to the multifaceted role of algae as: a first level food source, a provider of nutrients through photosynthesis, and, if grown in height (macroalgae like Kelp) or large numbers (microalgae like cyanobacteria), a provider of additional soft habitat. That is why in the overview, habitat producers are separated from habitat builders.

- **Macro producers**: Macroalgae, commonly called seaweeds, are marine plants that photosynthesize, but reproduce without flowers, and they are of a multicellular class. Their holdfast anchors their structure to a hard substrate.
- **Micro producers**: Microalgae, commonly called phytoplankton, are microscopic organisms that live in both the water column and sediment, and depending on their lifestyle, also attach themselves with their holdfast to other substrates. They exist individually, in chains or in groups. Individual microalgae are not visible to the eye, but can be seen through a microscope.

However, habitat producers are often much faster growing organisms than habitat builders, and if given the chance, they tend to overgrow a surface area. In that case, they leave little to no room for other habitat builders to settle and compete for space on the available hard substrate in the ecosystem, when in their larval state (Whalan et al., 2015). Additionally, when growing tall, macroalgae can limit the light availability of the

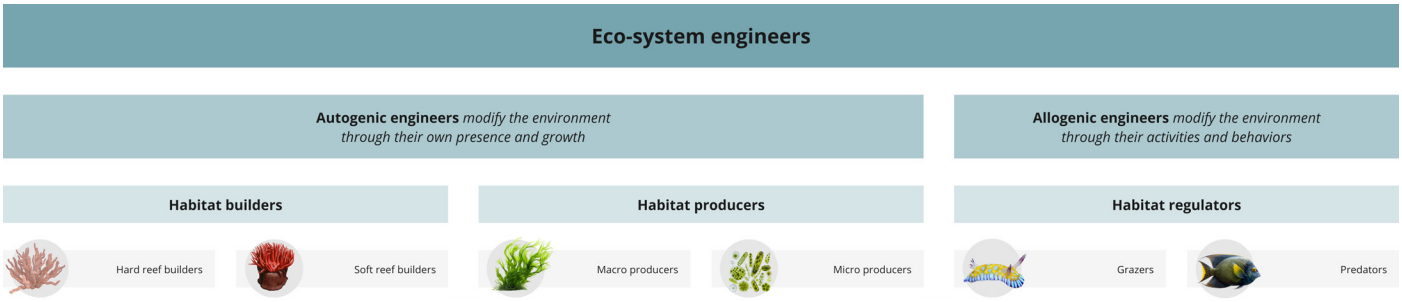


Figure 19: *Marine life overview of ecosystem engineers, including 'Habitat builders', 'Habitat producers' and 'Habitat providers'.*

organisms below it. Therefore, to maintain balance in an ecosystem it is important that the growth of algae is controlled, in order to leave room and allow light for sessile habitat builders.

Allogenic engineers

Allogenic engineers act as consumers across primary, secondary, and tertiary trophic levels and include herbivores, omnivores, and carnivores that control the growth of primary producers and each other (*Food Web*, n.d.). Therefore, mobile species that keep each other in check by grazing or predating will be further referred to as **habitat regulators**. Again, this is not a term used in literature, but I think that it perfectly comprises the roles of these species within the ecosystems to regulate the balance.

- **Grazers** are primary consumers and play a vital role in preventing habitat producers from overgrowing the entire reef by cleaning the surfaces of hard substrates, and making space for new organisms to settle (Little et al., 2009; Branch and Moreno, 1994).

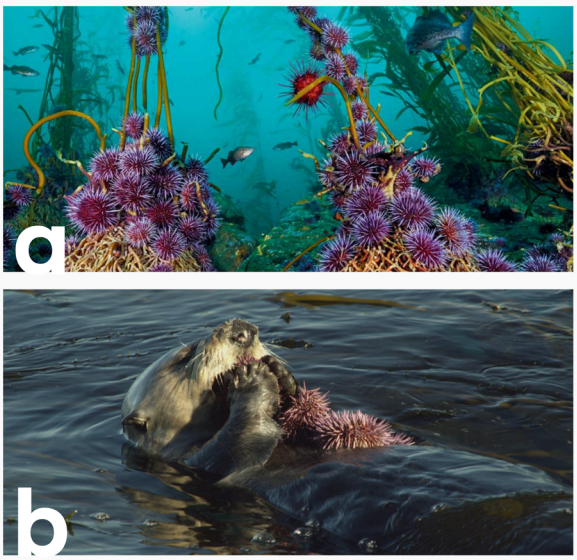
Similarly, the population of grazers must be controlled by their predators.

- **Predators** include both secondary and tertiary consumers and play a vital role in controlling the population of grazers, to prevent them from removing all habitat producers. In turn, larger predators control populations of other predators removing all grazers.

The **trophic connectivity** between the different levels of organisms that prey on grazers and other smaller organisms than themselves, ensures that a balance between growing and grazing habitat producers in the ecosystem is maintained.

A great example of the importance of the balance is illustrated by the relationship between sea otters (predators), sea urchins (grazers), and kelp forests ('habitat building' habitat producers), see Figure 20.

In conclusion, autogenic and allogenic engineers collaborate to shape the physical structure of their environment, and the balanced trophic connectivity between habitat builders, habitat producers and habitat regulators, whether sessile or mobile, ensure that the ecosystem they are part of remains healthy and stable (Figure 21).



Sea otters feed on sea urchins, which in turn graze on kelp. When sea otter populations were reduced due to human activity, the unchecked sea urchin populations devastated entire kelp forests, leading to the loss of habitat for numerous other species (Little et al., 2010). In contrast, if the sea urchin population were to disappear, the unchecked growth of kelp would create dense forests that, in time, will deprive other benthic species of their light availability entirely. Highlighting the importance of both predator and grazer populations in reef ecosystems and the intricate balance between them.

Figure 20: *Example of trophic connectivity with macroalgae, grazers and predators, with* ***a) A Kelp forest being eaten by urchins*** *(Tzu Chi Culture & Communication Foundation, 2022), and* ***b) An otter eating urchins*** *(The Urchin and the Otter | Big Pacific: Voracious, 2021).*

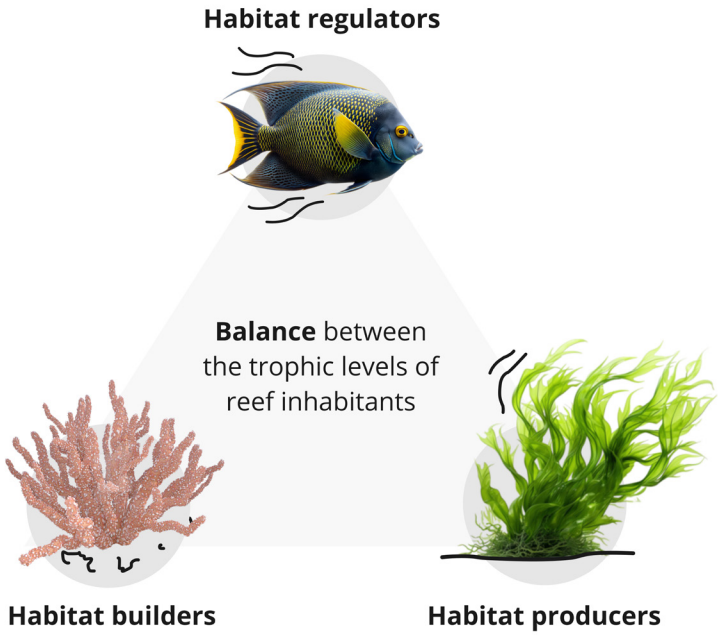


Figure 21: *Balance between Habitat builders, producers & regulators.*

2.2 | ReefBlocks

As described in the introduction, the structure of the ReefBlock is based on technical requirements for stability even in storm conditions (Figure 22) and modularity, while offering a home for marine animals through internally connected tunnels that provide refuge and shelter for larger marine animals, and through a surface pattern design that serves as a foundation for micro- and macro-organisms.

2.2.1 | ReefBlock contextual considerations

ReefBlocks are always stacked and grouped (Figure 23a), allowing for the most stable configurations resistant to extreme storm conditions (Figure 22). These configurations create additional tunnels for refuge and lee areas, where water is calmer, providing preferable conditions for some marine organisms (Figure 23b).

Wave energy is significantly higher on the frontal side where waves first hit the construction and much lower in the areas between and behind it. As waves collide with reef structures, the water is often most turbulent at the top of the reef and less turbulent towards the seabed (Figure 24). ReefBlocks are typically placed in subtidal areas at depths of 2,5-5m. But, as they are always stacked, parts of the blocks can also be considered within the intertidal zone, based on the environmental conditions they encounter when parts of them are above water. Tides may vary with about 1m, which means that the entire top ReefBlock may be exposed above water.

Similarly, sunlight exposure is highest at the top of the structure, with diminishing light availability as you go lower or between the blocks (Figure 25).

From these contextual observations, it can be concluded that the pattern will be exposed to variable environmental conditions, which can differ significantly per side, depending on the orientation of the ReefBlock and its position relative to the rest of the configuration.



Figure 22: *Scaled-down ReefBlocks showcasing the ability to withstand relatively extreme storm conditions, as a breakwater (credit: Reefy).*

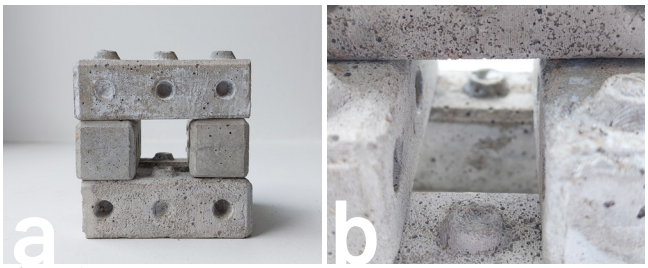


Figure 23: *Miniature ReefBlocks in configuration, with a) The most widely used configuration type by Reefy, and b) The lee area in between the block's configuration.*

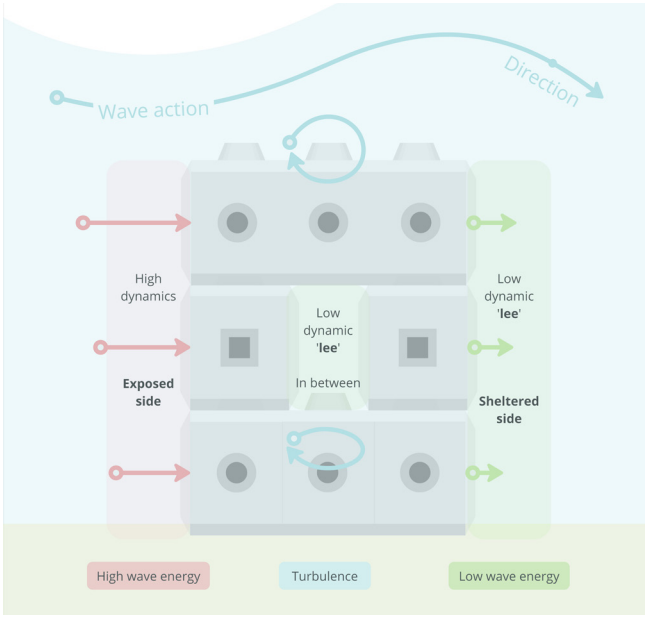


Figure 24: *Wave conditions around the artificial reef.*

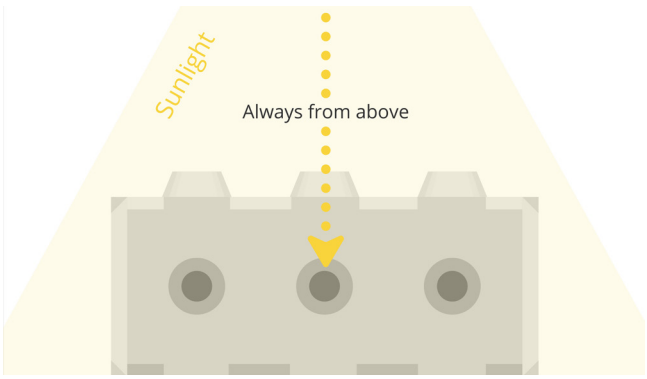


Figure 25: *Sunlight availability decreases from top towards the bottom.*

2.2.2 | Biodiversity index

To quantify the effects of their ReefBlocks, Reefy uses the Simpsons biodiversity index, a widely used metric in scientific studies (*Simpson's Diversity Index*, n.d.). This index is calculated by dividing the total counted number of organisms by the abundance of each species. It is often determined by manually counting and labeling organisms within a specific, contained area (Figure 27).



$$D = \frac{N(N-1)}{\Sigma n(n-1)}$$

D = Diversity Index
N = Total nr. of organisms
n = Population of each individual species

Figure 27: *Biodiversity index definition, and image showing how this is measured (image: Living Seawalls | REEF DESIGN LAB, n.d.).*

2.2.3 | Pattern application

As described, the sides of the ReefBlocks provide the opportunity to implement a surface pattern design. However, the available surface area for this design on the ReefBlocks is limited to designated areas as visible in Figure 28 (blue areas), which is a 2800x800mm surface area on the long side and 800x800mm on the short sides. The surfaces outside these pattern boundaries will remain smooth, as there will be no form liner inlay there due to the production method of the ReefBlocks.

Additionally, Reefy is interested in expanding their product line by applying the pattern design to 400 x 400mm panels that can cover existing or new quay walls in a repeating pattern.

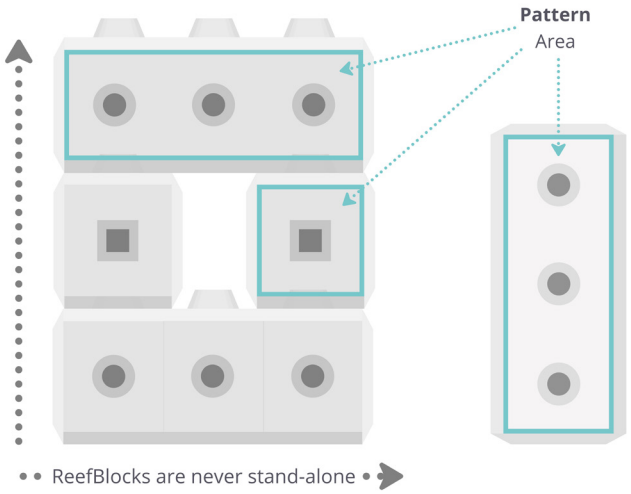


Figure 28: *Designated pattern areas on ReefBlocks, highlighted in blue.*

2.2.4 | ReefBlock production

The ReefBlocks are produced from recycled concrete and with Portland cement CEM-III, which is a marine-grade concrete widely used in marine infrastructure. When placed in water, large cranes carefully stack the blocks side-by-side (Figure 26).

This process emphasizes the importance of a pattern design that does not protrude or feature varying top surface depths, which could cause breakage during transport or destabilized stacked configurations of ReefBlocks. As the surface structure should ensure equal weight distribution.

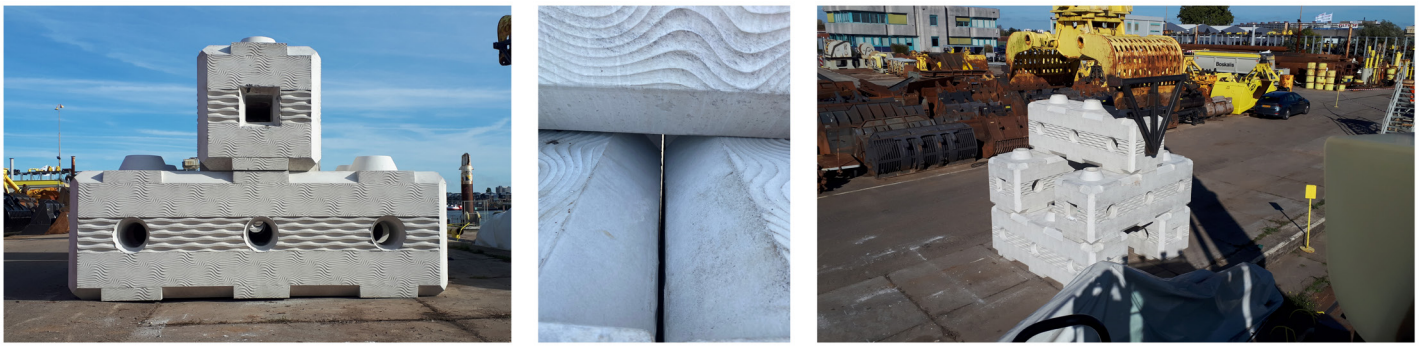
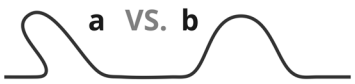


Figure 26: *ReefBlock placement.*

2.2.5 | Form liner production

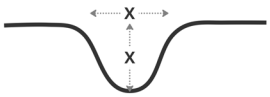
For the production of the ReefBlocks, form liners are inlaid into the mold before the concrete is poured. These form liners are produced by their external partner, Reckli, which specializes in form liners for various concrete applications. Reckli manufactures their form liners with PU rubber, which is a relatively cheap and durable material, if the design of the form liner meets a set of requirements:

No overhangs or undercuts



For the form liner design to be durable, it is important that there are no overhangs or undercuts (a) used in the design, as this will likely tear the form liner after only a few uses, so better to use protrusions like b.

Crevice width-depth ratio of 1:1



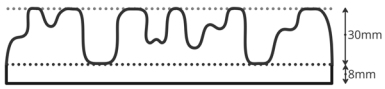
Another important point that will increase the durability, is that for every 1 cm a groove is in depth, it should be at least (or more than) 1 cm in width.

Rounded corners and edges



Additionally, the use of thin pillars is not recommended, especially with a base angle of around 90° (a), and so it is recommended to round off all corners with a fillet (b).

Depths no deeper than 30mm



This requirement is based on the currently used form liner for the deeper ReefBlock structure, as well as the thickness of the bottom of the form liner of 8mm. By keeping the same depth measurement, it is ensured that the proposed pattern design can be used in their current mold for producing the ReefBlocks. And additionally, the production costs for the form liner remain the same.

CAD model for digital fabrication

The form liner production process begins with the creation of a physical positive model, either through physical sculpting or digital modeling, such as 3D scanning or CAD modeling.

A digital CAD model, allows the form liner producer to translate the design into as many physical models as necessary, using digital fabrication techniques, such as 3D printing or CNC machining. These fabrication methods are common in concrete formwork due to their precision and consistency.

Similarly, Reckli uses a CNC machine to carve a positive 'mother 'mold from a material, which is then used to create as many custom negative rubber form liners as needed for the production of ReefBlocks. By providing a digital CAD model of the final proposed design, Reckli is easily able to produce such a positive 'mother mold'.

The rubber form liners are placed inside the molds to ReefBlock to imprint the desired surface texture and structure into the poured concrete on all five visible sides of the block.

2.3 | Stakeholders

Reefy

The project's client, a start-up company, based in Delft and Mexico, that combines hydraulic engineering with marine biology in a product that combines coastal protection and marine life conservation. They offered me this assignment with clear parameters for the project: a pattern design that is integrated with their current ReefBlock as well as that can be used for additional (future) wall panels for biodiversity enhancement. They expected me to create an aesthetically pleasing pattern design that is desirable for the general public and creates a good representation of their brand. They do not have a (product) designer in-house, and so that is my added value to them in this project. Design decisions and implementations about the feasibility, as well as the viability, with regards to marine life, were discussed and chosen together with Reefy, based on their in-house knowledge on these subjects as well as with interviews with their production partner and an external marine biologist.

TU Delft

The university is where I need to showcase the skills to officially become a MSc. Industrial Design is represented by my chair and mentor, who have guided me through this project with weekly meetings. My chair Joana Soares Martins is involved with micro-algae research which has led to the addition of micro-algae testing in a lab environment to verify the results of the final pattern design to some extent. Additionally, for these microalgae testing the facilities of the TU Delft were used. The microalgae tests were conducted in the IDE Biolab and with microalgae strains from the lab, as well as investments in equipment, approved by the lab's supervisor, for two aquarium setups, which could be used for future experiments. My mentor Caroline Kroon is part of the Sustainability department, which is part of the TU Delft's ambition to create a more sustainable future with regard to the Sustainable Development Goals. This project is right up that alley, as it involves the conservation of marine life below water (UN SDG 14: Life below water).

Reckli

This company is the production partner of Reefy who produces the form liners that are used for production of the ReefBlocks. The influence of Reckli is mainly with regards to the limitations of their production technique. By means of an interview they provided me with the relevant information that helped me in making design decisions further in the project.

Worldwide authorities and developers

The targeted buyers of the ReefBlocks are governments, water authorities and private asset owners and developers, such as high end resorts, all over the world that want to protect their coastlines for e.g. beach and asset protection, and regenerate reefs to preserve local ecosystems and help attract tourists for diving. This means that the targeted areas range from warm to temperate climates, with varying coastal ecosystems. These stakeholders will mainly concern themselves with the aesthetics of the ReefBlocks: does it look good visually? And on the story around that aesthetic: why does it look the way it looks and why is that good?

Marine life

As described in Chapter 2.2, the ReefBlocks will be placed in a variety of locations and climates. This means that the targeted marine life for this project is kept very broad, namely, all marine life. However, the interactions that take place between different categorizations of marine life (which exist everywhere in the world) can be analyzed and combined into one design, with the variety of aquatic contexts and important functions of a reef in mind. Existing knowledge about marine life and artificial reefs helped and influenced me in making design decisions during this project.

3

Literature review

This chapter discusses the current state-of-the-art knowledge on artificial reef structures and the unraveling of what is known in literature about specific design features that promote biodiversity.

The literature review was split for the structural design features on centimeter scale and the surface texture on millimeter scale.

The main conclusion from literature with regard to the surface structure was that the addition of any complexity and heterogeneity may increase biodiversity.

In particular the use of design features such as deep crevices, pits and rock pools were considered as the most important factors for biodiversity enhancement, even above material composition.

With regard to millimeter scale texture, the use of regular grooves increased larval settlement of habitat builders the most.

The most important insights for the structural features were concluded in a micro/meso marine spatial planning schematic on top of the ReefBlock (Figure 29):

- Pits in varying sizes, equally distributed.
- Focus of vertical crevices on the top half.
- Focus of horizontal continuous crevices in the middle of the pattern.
- Focus of horizontal intermittent crevices on the bottom half.

The most important insight for the surface texture was concluded in a 'height map' with regard to mimicking 3D printed like layers.

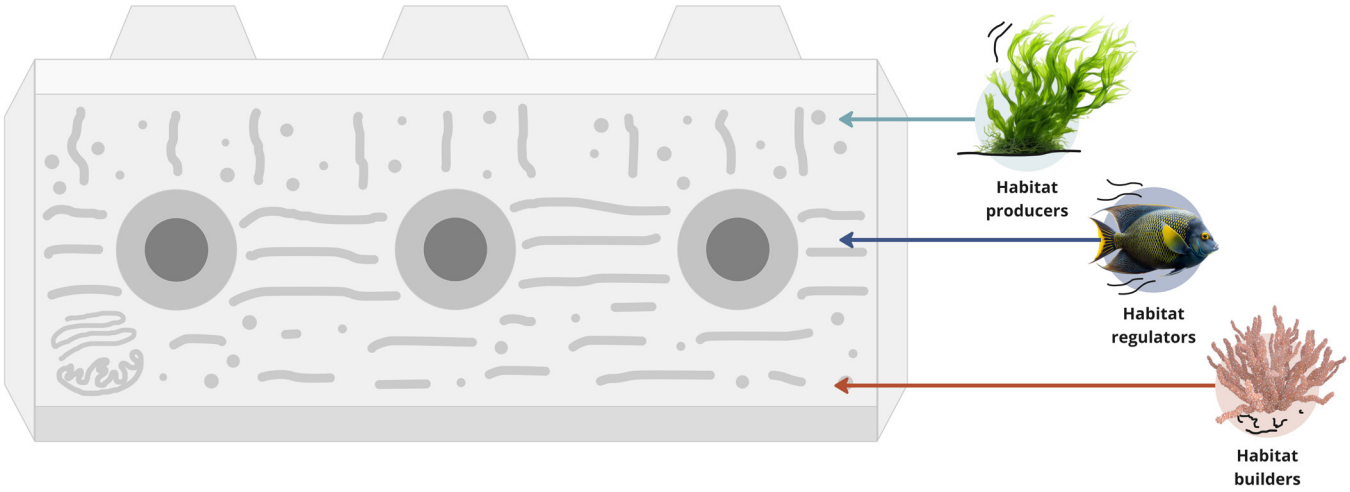


Figure 29: *Schematic of the ecological and easthetic requirements visualized on the ReefBlock.*

3.1 | Existing solutions

Artificial reefs have been around for centuries. Either built deliberately by humans or unintendedly sunk to the bottom of the ocean in the form of, for example, shipwrecks. Artificial reefs are built for the following two main reasons (National Geographic, n.d.) relevant to the context of this project and similar to the ReefBlocks (Figure 30):

1. To protect the coastline and beaches from erosion, based on the natural function of reefs as breakwaters that reduce wave energy before reaching the shore.
2. To promote and restore reef ecosystems, based on the natural function of reefs as habitats and 'boosters' for marine life abundance in and around the reef ecosystem. Which actually serves both nature and humans.

Biodiversity attracts more biodiversity and supports marine life abundance on all trophic levels, among which, fish and other invertebrates. And the more abundant the presence of such invertebrates, the more food availability there is for human fishing activities. Some artificial reefs are specifically made for cultivating and harvesting for the food industry.

Additionally, beautiful reef structures and their abundant reef community are a great attractor for diving tourism. However, the presence of this type of tourism can be destructive to reef ecosystems, due to divers (accidentally) destroying reef structures and chemicals leaching in the water from their sunscreens.

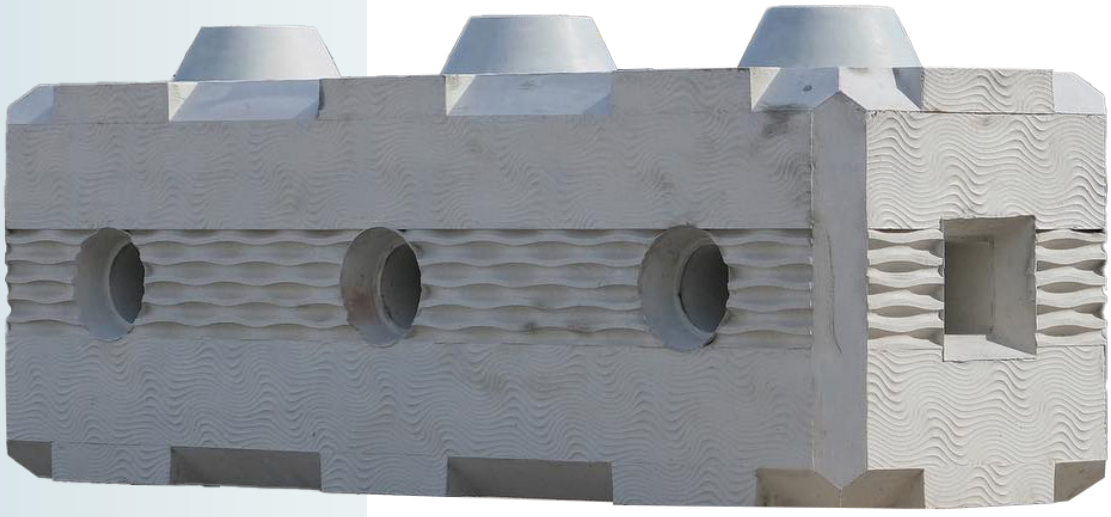


Figure 30: *Existing solution: the current ReefBlock.*

3.1.1 | Benchmarking existing artificial reefs

In recent years the main focus of artificial reefs has been to restore lost habitats of reef communities due to destruction by human activities or replacement of habitat by homogeneous marine infrastructure, as discussed in the introduction. In addition to this, research is starting to emphasize the importance of considering the artificial reef as a part of a broader 'network' of connected ecosystems.

In the field of artificial reefs there are diverse examples that have been tried and tested over the years. Some proved to be more effective than others and some were later even proven to have detrimental effects on marine life. For this project, I compared a number of different existing solutions within the field of artificial marine reefs (Figure 31) and benchmarked them based on (see Appendix B for the complete overview):

- Production technique & material use
- Intended marine life & environment
- Implemented design features & visual elements
- Measured effects & effectiveness

Highlighted examples

The construction of off-shore infrastructure like rigs can be disruptive during the build, however their bases introduce hard substrates for reef communities to take advantage of, in soft sediment environments. There are cases where decommissioned off-shore rigs are carefully being tilted on their side, and this way are used to form so-called "Rigs-to-Reefs" (Figure 31a). This type of reef has been explored by literature and seems to have a positive effect on ecosystem functioning, given time.

Similarly, there have been a multitude of projects that deliberately sunk metal vehicles into the ocean, such as buses, tramways, tanks or boats, much like the early shipwrecks (Figure 31b). A well-known example of a disastrous attempt to create artificial reefs out of unused products is the Osborne reef (Figure 31c). It was 'built' from 2 million discarded tires that were chained together and dumped in the ocean. Later it turned out that the chains had broken, which means that all individual tires are being dragged by waves across the seabed, potentially destroying the reef community attached to it or other reefs on their path to this day (Chad, n.d.). Even more, the tires are quickly subjected to sedimentation due to their low height and

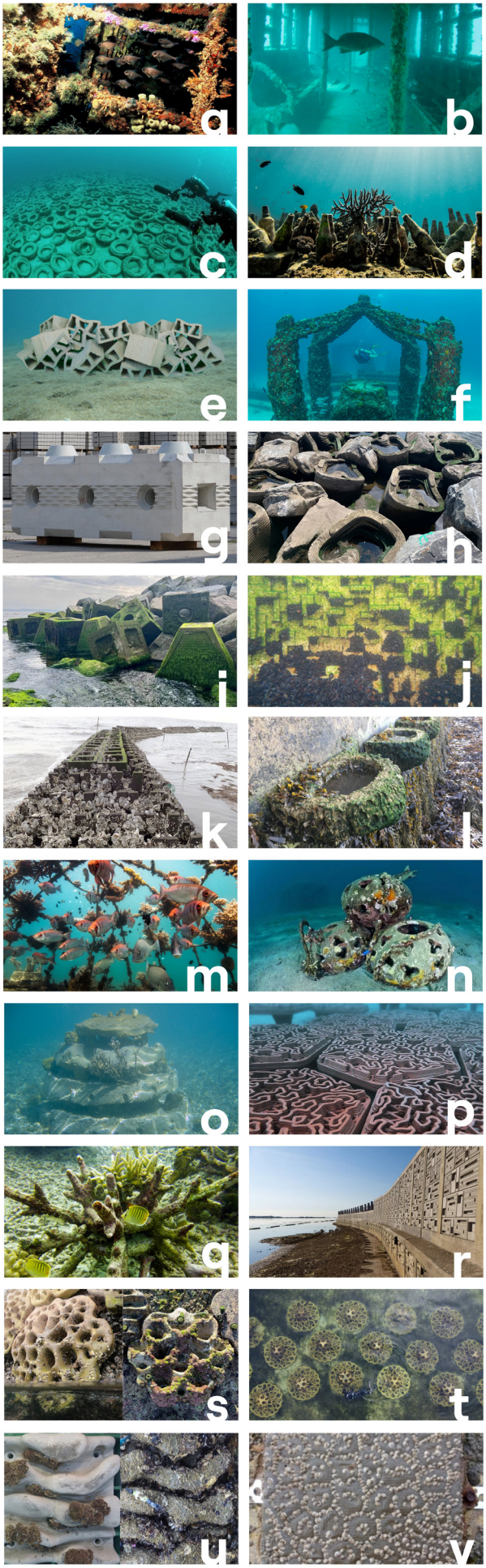


Figure 31: Overview of existing solutions. *Images: a (Carlson, 2017); b (Boldwater, 2020); c (lupusart.net, n.d.) d (Correspondent, 2019); e (Oyster Heaven, 2024); f (Swimming in a Cemetery of Human Remains., n.d.); g (Reefy); h (Crook & Crook, 2023); i (Bryant, 2024); j (ECOncrete, 2024); k (Miller, 2022); l (Artecology, 2024); m (Netherlands, 2021); n (Reef Ball Styles, n.d.); o* (Hylkema et al., 2020); p (Board, 2023); q (Cornwall, 2022); r (Portsmouth Flood Defences, n.d.); s (Living Seawalls | REEF DESIGN LAB, n.d.-b) t (Hui, 2024); u (Ushiama et al., 2019); v (Encrustations : Multispecies Design, n.d.)

horizontal orientation and generally don't seem to support many marine organisms. This example highlights the importance of sturdy, anchored artificial reefs with a more vertical orientation.

Other recreational attempts of artificial reefs are being tried on local scales. Some involve small constructions of glass bottles or cinder blocks (Figure 31d-e). And others are used as an art installation that is meant to function as an artificial reef. Most of these are made with concrete, since this material is easy to mold into any shape. And few of such installations even incorporate the ashes of people's loved ones in the concrete, as a sort of underwater graveyard, such as Neptune Memorial Reef (Figure 31f). Next to these examples, there are also many commercial examples of artificial reefs emerging (Figure 31g-v). Most existing commercial solutions offer proven effective methods to increase species richness in otherwise more barren areas with low biodiversity, based on or even as part of scientific studies. Which makes them great sources of inspiration for my project. Most of the examples are at the basis simple geometrical shapes with added complexity in different forms, such as (floating) reef balls, reef cubes, 'layered-cakes' or retrofitted wall panels (Figure 31).

3.1.2 | State-of-the-art knowledge on artificial reef structures

Artificial reef ecosystem functions

In general, any addition of a hard substrate in bare sand habitats will likely result in an increase in (micro) habitats and shelter availability (Hylkema et al., 2020), which will positively influence **species richness** (the number of different species) and the **species abundance** (the total number organisms of each species present). However, the magnitude of that positive effect of artificial reefs is determined by the variety of **trophic levels** the ecosystem provides microhabitats for (Schram et al., 2024). **Microhabitats** are facilitated by specific **design features** in the artificial reef, representing smaller sheltering or feeding areas within the ecosystem (on meso level), each with their unique conditions that may be home to unique species, and that may not be found in the larger region (*Reef*, n.d.). The ecosystem habitat (on macro level) determines the distribution of microhabitats in relation to each other. This distribution determines what type of inhabitant will likely live or interact with the ecosystem and where these interactions will take place. An equal distribution, or patterning determines the functioning and productivity of an ecosystem (Pringle et al., 2010). Thus, to effectively create reef ecosystems, it is essential to design artificial reefs that consider not just their **patterning** structure and texture, and material, but also their functionality in enhancing trophic connectivity and species growth, creating a "true marine forest" (Bracho-Villavicencio et al., 2023). And in order for me to understand what is known in the field of artificial reefs, I divided my research based on the different ecosystem functions with regards to: trophic connectivity between the inhabitant types (identified in Chapter 2.1) on macro level, providing shelter to organisms of all sizes on meso level, and the recruitment of autogenic engineers on micro level.

Macro level: Trophic connectivity

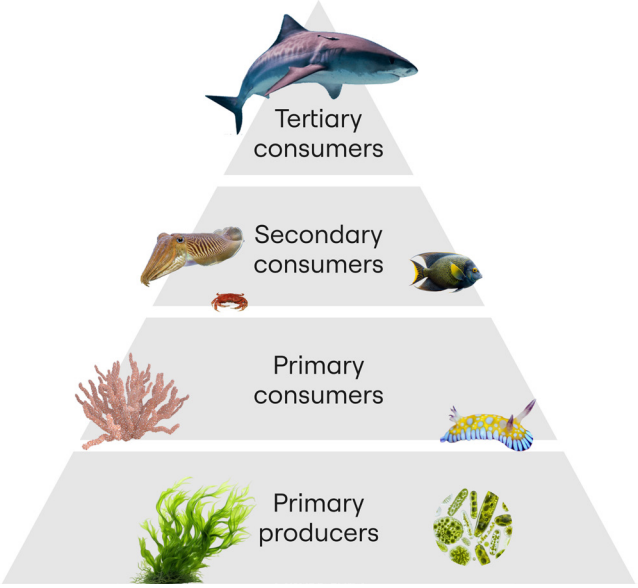


Figure 32: *Repeated marine trophic levels.*

Artificial reefs can play an important role in facilitating trophic connectivity in addition to their intended ecosystem (and economic) functions (McLean et al., 2022). **Trophic connectivity** refers to the fact that each inhabitant, regardless of type, plays their role in the food web of their specific reef community, to eat and to be eaten (Figure 32). This includes habitat producers, which produce nutrients and are eaten by grazers, and habitat builders and regulators, which consume smaller organisms and are preyed upon by larger organisms, who are in turn eaten by even larger organisms, and so on. Balance between the three types of inhabitants in the ecosystem is important to build and support productive reef communities.

As discussed, each inhabitant type must be accounted for, as well as an equal distribution of the three types over the surface area of the ReefBlock (Chapter 2.2). These trophic interactions are the main predictors for the success of the artificial reef as biodiversity enhancement, and are the main drivers for this research, on

which the requirements for the pattern design will be based. The trophic interactions between inhabitant types and the ecosystem functions is similar for every ecosystem, regardless of environment (Chapter 2.1).

Within seconds, any surface, regardless of how smooth, immersed in ocean water becomes covered with a thin film consisting of macromolecules. Over time, more cells are adhered to the surface and a so-called **biofilm** starts to develop (Flemming, 2002). In literature, biofilm formation is often referenced with a more negative formulation, as *biofouling*, as in many marine contexts biofilm formation is undesired. Fortunately, biofilms contribute to the biodiversity and ecosystem processes of aquatic ecosystems, as pioneer microorganisms (that form the initial biofilm) facilitate the settlement of next arrivals, such as cyanobacteria, micro- and macroalgae (Hayek et al., 2022). Thus, **bio-receptivity**, the ability to be colonized by living organisms, is the ultimate goal of artificial reefs.

As grazers consume the microorganisms on the surface of an artificial reef, they help regulate biofilm formation, which in turn affects nutrient cycling and ecological succession in the ecosystem. And additionally, these grazers attract larger species to the reef ecosystem, as they serve as prey for higher trophic levels. These interactions link a wide variety of species across the different trophic levels by facilitating both grazing and predation.

Meso level: Providing shelter

The most important structural qualities associated with higher species richness and abundance of species, as mentioned in many studies, are complexity and heterogeneity in the artificial reef on both meso and micro level. With **complexity** referring to structural design features, including pits, crevices or tunnels, that provide for specific ecosystem services, such as shelter, refuge or specific sunlight availability. And **heterogeneity** refers to the variety of available sizes of such structural or textural features, to support a wide variety of reef community species in different life stages and sizes.

Added complexity and heterogeneity in the structural design features of artificial reefs or seawalls, simultaneously increase the available surface area (Loke and Todd, 2016) which allows for more settlement of all ecosystem engineers, reduce predation on both sessile and mobile species (Strain et al., 2018; Ushiama et al., 2019), and increase survival of sessile species as they expand the range of available abiotic conditions in the ecosystem (Chee et al., 2020; Perkins et al., 2015).

Different species have different needs for 'ideal' complex design features. Sessile photosynthetic species, like the habitat producers, need to maximize their light availability and tend to have less competition for space on smooth surfaces. Sessile filter feeding species, like most habitat builders, need water flow in order to have sufficient and constant food supply, while they also need to make sure that they are sheltered as much as possible against predation, as they cannot move away from predators. Mobile species, like the habitat regulators, may interact temporarily with the artificial reef for safe breeding, for foraging and predation of the trophic levels below them, or for refuge from the trophic levels above them.

Within the same categories of inhabitants, and even within the same species, a wide range of sizes and shapes of marine life, depending on their life stage and lifestyle, will want to interact with the available surface area of the artificial reef. And in order to increase the attraction and support of a wide variety of unique species, habitat heterogeneity of the design features is essential (Bishop et al., 2022) and is best achieved with structural features that are closer to the targeted body sizes (Hylkema et al., 2020; Strain et al., 2018).

Multiple studies observed that the sizes of the design features directly influences the size range of the present inhabitants (Schram et al., 2024; Ushiama et al., 2019). Natural reefs typically offer a great abundance of millimeter-centimeter scale 'refugia', ideal for smaller-bodied inhabitants, whereas some larger artificial reefs (like ship hulls) provide only centimeter-meter refugia, attracting mainly larger-bodied inhabitants. The targeted body sizes of our inhabitants that will interact with the surface structure can range from <1mm, like larvae, to <50mm small mobile species, up to >50mm larger mobile species (De Brauwer et al., 2019; Ushiama et al., 2019).

Large-bodied species will likely only interact with the artificial reef for feeding activities (Baine, 2001) and they can exert considerable top-down control on the community structure on the artificial reef (Strain et al., 2018). The presence of sessile marine life attracts such large species to the reef, and shallower surface topography allows them to better reach their prey (Ushiama et al., 2019). Whereas in contrast, habitat complexity can significantly reduce predation on key sessile habitat builders (Bradford et al., 2020; Strain et al., 2018).

Scientific literature reportedly refers to design features that are representatives of natural substrates

(Bracho-Villavicencio et al., 2023; Loke and Todd, 2016; Perkins et al., 2015; Salauddin et al., 2021), which is materialized by effective design features such as: crevices, pits, grooves, towers, ridges, overhangs, and so-called rockpools.

In most case studies, the addition of crevices and pits showed the greatest increase of small-bodied species in both vertical and horizontal surfaces (Bishop et al., 2022; Firth et al., 2014; Loke and Todd, 2016; Paalvast, 2011; Strain et al., 2018). Nonetheless, on vertical surfaces the effects of the same design feature can be very different from horizontal surfaces (Paalvast, 2011; Evans et al., 2021; Chee et al., 2020).

Vertical surfaces provide protection against both heat exposure and against predation. Especially deeper design features like crevices and pits, ensure that parts of the surface area are shaded, which helps to keep the overall temperature to be lower (Perkins et al., 2015). By providing greater topographical heterogeneity, as associated with many natural vertical rock surfaces, a larger range of temperatures across a thermal gradient is available on the intertidal zone to meet the needs of different species (Perkins et al., 2015). Strain et al. (2018) listed the most effective design features to implement in artificial substrates, based on a qualitative review of 109 studies worldwide, and they grouped the results for the intertidal and subtidal zones and for different types of marine life. In the intertidal zone, features like crevices are mostly linked to increase of sessile species, and pits increase both sessile and mobile species. Whereas in the subtidal zone, these features mainly increase the abundance of smaller-bodied mobile species, and surface (millimeter-scale) texture enhances the coverage of sessile species (Strain et al., 2018). However, specifically the addition of pits had the greatest benefits for multiple groups in both the intertidal and subtidal according to the studies (Strain et al., 2018). Structurally, the addition of pits is most similar to fossilized corals that provide a great substrate for next generations, as well as the void spaces in between other hard reef builders, like oysters, mussels or barnacles.

In the intertidal zone, the addition of microhabitats at the scale of 10–50 mm in depth and widths, improves species richness and abundance on hard vertical surfaces in the intertidal zone, by providing habitat for species that would otherwise be absent (MacArthur et al., 2019; Coombes et al., 2015; Bradford et al., 2020). However, crevices between 25-50mm are more productive for a wider range of species (Bradford et al., 2020). Additionally, Reefy has noticed in checks on biodiversity with their current design that the deeper pattern, which creates a more crevice-like feature, has a much greater species richness and abundance than the shallow pattern. Therefore, crevices in the range of 10-50mm in width are interesting target sizes, with a slightly more abundance of crevice with widths in the range of 30-50mm; taking into account that the production technique of ReefBlocks limits the depth at 30mm (see Chapter 2.2.5).

Whereas, horizontal surfaces will have much greater species abundance, when they retain water or sediment, due the presence of rockpools created by pits or 'intermittent' crevices (Evans et al., 2021; Bishop et al., 2022). Moisture retention on the surface structure helps keep the mean temperatures lower (Loke & Todd, 2016), and the deeper the rockpool, the lower the water temperature (Chee et al., 2020). However, regardless of depth, species abundance is higher on the vertical side surfaces than at the bottom surfaces of the pools. Bottom surfaces, that are exposed to more sunlight, were covered with algae, as opposed to the sides of these pools that were covered in a higher variety of both sessile and mobile species (Chee et al., 2020). However, such rockpools can have the incidental function as sediment instead of water retention, depending on the location the artificial reef structure is placed, which can extend the available habitat for benthic species on higher grounds (Bone et al., 2022). Even though it may be beneficial for some (mobile) benthic species in the intertidal zone. In the subtidal zone, the addition of large rock pools should perhaps be avoided on vertical surfaces, since the retention of sediment can be suffocating for sessile (filter feeding) habitat building species.

Additionally, horizontal surface textures with more concave rather than convex features are found to be better for biodiversity (Evans et al., 2021). Reflecting the value of water-retaining features, even at the mm–cm scale (Firth et al., 2014; Salauddin et al., 2021).

Micro level: Recruitment of pioneering organisms

Without the presence of habitat builders and producers an artificial reef will not likely become a thriving biogenic reef over time. As these inhabitants are considered the pioneering species that must be attracted first, in order to attract habitat regulators that search for food and shelter. Therefore, it is important that recruitment of such marine life is promoted through the artificial reef structure. The presence of habitat builders and producers on artificial reefs can be influenced or deter-

mined in two ways:

1. Through recruiting habitat builders in their larval stage or habitat producers in their algal spore stage, with micro-topography;
2. Through 'seeding' the artificial reef with mature habitat builders or producers, by gluing them on permanently before placement.

At the beginning of their lives, habitat builder larvae (or spat) are microscopic, mostly planktonic organisms similar to the size range of single algal spores. This also means that both are near or at the bottom of the food chain and are always in danger of being eaten. A great way for them to avoid this faith, is by attaching themselves to hard substrates that can protect them while they are able to grow bigger. Rough surfaces are more prone to microbial colonization than smooth surfaces (Flemming, 2002). Therefore, it is argued that surface roughness is the most effective parameter to promote bio-colonization of cementitious materials, and more specifically with the use of slag cement type CEM III (Hayek et al., 2022). Which is exactly the type of Portland cement that Reefy uses to produce their ReefBlocks in Europe, as it is a widely used cement type for marine contexts. Surface roughness is thought to have an overriding influence on settlement of microorganisms, over f.e. chemical composition or color, with regards to active larval searching behavior, recruitment and post-settlement survival of many micro-organisms, as these are directly influenced by the attachment strength and shelter opportunities a surface provides (Coombes et al., 2015). Hard substrates are better at providing a stable attachment surface compared to soft materials, which is beneficial in a turbulent environment like an ocean (Erramilli & Genzer, 2019). In turn, "most scientists agree that marine organisms adhered to the concrete surface form a bio-protection layer against chemical attack in seawater; as they form a physical barrier that reduces surface permeability" (Hayek et al., 2022). This helps to further argue for the benefit of hard substrate (concrete) artificial reefs.

But, to understand what the ideal conditions are that microscopic organisms need, a lot can be learned from papers that discuss 'antifouling' techniques, and to go against their advice on what not to do (Erramilli & Genzer, 2019; Scardino et al., 2006; Flemming, 2002). Surface textures at micrometer-scale play an important role in larval and algal spore settlement (Coombes et al., 2015; Erramilli and Genzer, 2019; Long et al., 2010; Scardino et al., 2006). Surface topography that is comparable to or slightly larger than the organism, allows the organism to create as much contact area with the surface as possible. Which maximizes their attachment, due to the increase of van der Waals forces for effective adhesion (Erramilli & Genzer, 2019; Scardino et al., 2006). In contrast, micro-topography smaller than the overall size of the micro-organism has the least amount of settlement (Erramilli & Genzer, 2019).

However, the average size of algal spores and that of habitat builder larvae is different. Meaning that they will respond better to different scales of micro-topography. As discussed, many algae types generally grow much faster than many of the habitat building species (Whalan et al., 2015). The formation of microalgal biofilms, or so-called turf mats when they have grown thick, actually compete with the habitat builder larvae for available space, and they will likely overgrow the larvae in no time. Which is why it is important to prevent algal spores from taking over the entire surface area of an artificial reef, while still supporting grazing activities by habitat regulators in specific areas.

For instance, the settlement of diatoms, a type of micro-algae in the size range of 170 to 260µm in length, significantly decreased with topographical features in the range of 100 to 250 µm (Erramilli & Genzer, 2019). From this research it can be concluded that surface features smaller than 0.2 mm, especially with asymmetric topography, are discouraged for artificial reefs. With research pointing to existing natural antifouling strategies, such as the skin of sharks and the self-cleaning properties of lotus leaves, as optimal models (Erramilli & Genzer, 2019). Algal spore settlement is affected by the topographic pattern and is mostly concentrated at the intersections of features, compared to asymmetric features (Long et al., 2010). Which confirms what Erramilli & Genzer (2019) discussed with the examples of natural antifouling strategies.

A research by Potet et al. (2021) compared oyster larvae recruitment on ten different surface pattern designs, as well as comparing them with two material compositions, in the subtidal zone. Based on these comparisons, they confirmed only weak effects of material composition, but again, strong effects of micro-topography of the surface pattern. They even accounted for the position compared to neighboring tiles, and found that recruitment density was determined by surface topography over position on the grid, as two neighboring tiles could have huge differences. And they tested the same tile designs positioned in different orientations and positions on multiple grids. The texture that performed signi-

ficantly better is the one that looks the most like natural (weathered) stone. Potet et al. (2021) revealed with their study a positive correlation between surface roughness at millimeter-scale, with **topographies around 1mm**. They argue that "surface roughness [...] closer to the oyster larvae size, is presumably linked to a 'protection' mechanism, i.e., camouflage, against predators during the sensitive period of metamorphosis" (Potet et al., 2021). In confirmation to this, they revealed a strong larval preference for settlement on sidewalls and in pits or valley bottoms, whereas settlement on exposed flat areas on the tops was very low. Which shows that when habitat builder larvae settle, they rather avoid highly exposed areas and settle on more shadowed and protected areas. Other studies also reveal that the best profile for oyster and barnacle larvae settlement is intermediate concavity in a regular grooved finish (Johnson, 2017; Coombes et al., 2015).

Additionally, seeding the artificial reef structure before placement can have a significantly positive effect on the biodiversity richness and abundance (Ushiama et al., 2019; Bradford et al., 2020). Seeding with mature habitat builders more likely increases settlement or survival of larval recruits of the same species, as well that it has a significant effect on the coverage of other sessile organisms, even on a previously flat, homogenous tile (Ushiama et al., 2019). Even more, as seeding with a desired native sessile species can 'kick-start' and increase the settlement of their own kind, the dominance or colonization of an invasive (non-native) sessile species can be better prevented via competition for space (Bradford et al., 2020).

Targeting the presence of specific sessile filter feeding species, like most habitat builders are, on artificial structures with seeding can significantly enhance the colonization of more species, driven by successional processes (Whalan et al., 2015). Such changes not only promote biodiversity but also potentially expand the range and magnitude of ecosystem functions and services (Bradford et al., 2020). For instance, increased filtration activities by these filter feeders can improve water quality (scan the QR code for a video that shows this process), benefiting the overall marine environment (Bradford et al., 2020). Furthermore, research indicates that mobile species often exploit the microhabitats created by seeded bivalves or shells, providing them with essential shelter and foraging opportunities (Firth et al., 2024). Therefore, seeding can be a great opportunity to target desired (native) species in the reef ecosystem. For this, specific 'seeding holes' could be added to the structure, in order to facilitate the addition of so-called 'reef plugs'.

Conclusion

Some of the examples of artificial reefs in the benchmarking overview actually have this effect implemented. For example, the EMU from Reef Design Lab (Figure 31t) or Moreef (Figure 31p) are 3D printed structures, produced with a ceramic material which creates thick and distinctive layers (layer height around 3-6 mm). The Living Seawalls (Figure 31s) are produced with formliners casted from 3D prints, which means that the thin 3D printing lines (layer height around 0.2-0.4mm) are casted along when the concrete is poured in the mold. These examples created a great inspiration for me, to utilize this artifact of 3D printing to the benefit of marine life.

3.2 | Meso and micro marine spatial planning

Spatial planning is a term from architecture that refers to the organization of planned use and design of a living area, aimed at influencing the future spatial distribution of activities and a balanced development that meets the functional objectives (Yoshida et al., 2020). Reefs can be considered small to large underwater cities with unique reef inhabitant communities that provide different ecological functions at the meta, macro and meso levels. Concluding from all the information found about artificial reefs and marine life preferences, I concluded micro marine spatial planning in a height map for the surface texture (Figure 33) and meso marine spatial plannign for the surface structure (see next section).

3.2.1 | Micro marine spatial planning

For the height map, it is important to adapt it to the natural behaviors and preferences of the different inhabitants:

1. **Top layer (depths of 0-10mm)**: Habitat producers need most light and will likely occupy the most protruding features with smooth surfaces.
2. **Middle layer (depths of 10-20mm)**: Habitat builders need access to light, while remaining sheltered and in less need to compete with habitat producers for space. Also, their larvae need millimeter-scale surface textures for settlement.
3. **Bottom layer (depths of 10-30mm)**: Habitat regulators need shelter, yet they are in no need of additional surface texture.

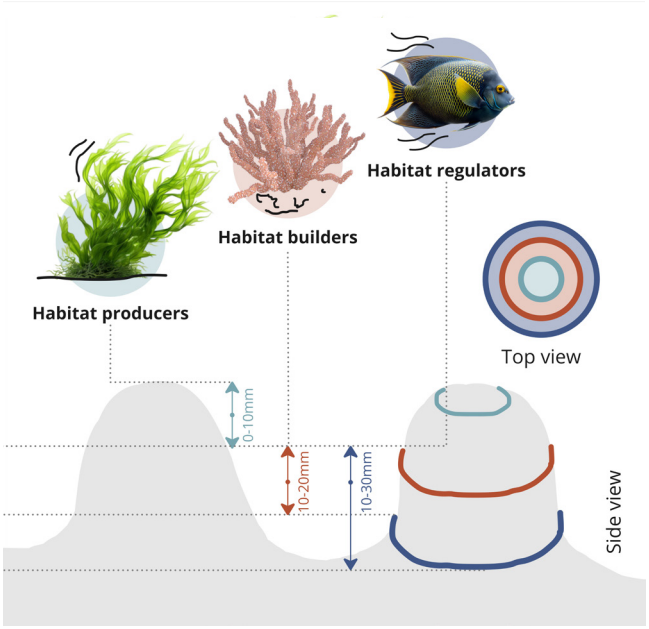
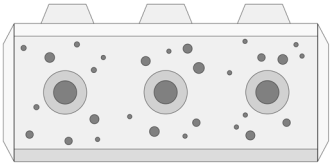


Figure 33: *The 'heightmap' of the surface pattern design, with regard to the reef inhabitants.*

3.2.2 | Meso marine spatial planning

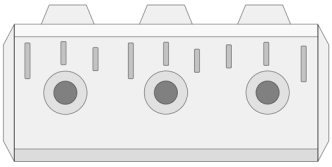
The following key design features are defined to distribute over the surface area and enhance the ecological function of artificial reefs:

Pits in varying sizes, equally distributed over the surface



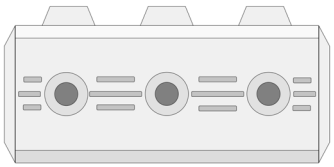
These pits in varying sizes allow for both habitat builders and regulators to find a more confined comfortable place to settle. Especially, as both of these types are found to often seek shelter in a pit close to their own body size. Additionally, pits form rock pools on a horizontal top surface, allowing for better moisture retention in the intertidal zone.

Focus of vertical crevices on the top half of the pattern



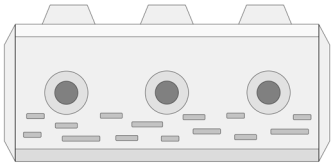
These vertical crevices (on a vertical plane) actually allow algae to adhere, because less shadow is created. However, barnacles will likely inhabit the more shadowed sides as these will be less occupied by algae. The vertical crevices also provide a good supply of water flow, which is preferred for many filter feeding species. Furthermore, the exposed areas in the vertical orientation also provide easier feeding ground for larger predators.

Focus of horizontal continuous crevices in the middle of the pattern



These continuous horizontal crevices provide longer 'lanes' for both small fish to refuge in the depression and for algae to cultivate longer lanes on the protrusion, right in the middle of the block, facilitating easy grazing activities by various grazers. Additionally, this design feature was partially decided for aesthetic reasons, making the pattern seem more integrated with the ReefBlock's structural holes.

Focus of horizontal intermittent crevices on the bottom half of the pattern



Horizontal crevices form protective overhangs that increase the likelihood of habitat builders developing there. A higher abundance of habitat builders at the bottom allows for the biogenic reef to develop in a more pyramid-like shape, enhancing stability and allowing for light availability for higher organisms. The higher number of separate horizontal micro-habitats may also allow more habitat building species to coexist next to each other, as these may colonize crevices with their unique abiotic conditions, compared to continuous crevices that may be entirely colonized by more of the same species.

Focus of smoother surface textures (eroded, like fossilized coral) on the top half

This design feature promotes algae growth more focused at the top half. Underwater, many of the macroalgae have air pockets that help keep them upright to be exposed to sunlight as much as possible. Above water, these macroalgae hang down due to gravity. This 'behavior' of (macro)algae benefits the ecosystem, as hanging algae protect the marine life below by keeping it moist and more shadowed.

Focus of rougher surface textures (representative of living coral) on the bottom half



By better representing the textures of living corals, the larvae of habitat builders can settle in the millimeter-scale grooves that are closer to their body size, rather than the size of algal spores (for which the finer textures are intended).

3.3 | Overview of most important requirements

Concluded and acquired from Chapters 2 and 3, the list of most relevant requirements which I used for designing a pattern for biodiversity enhancement, divided by the three main pillars of this project: ecological, ReefBlock and stakeholder requirements (for the complete list see Appendix C). Figure 34 shows a visual representation of the ecological and aesthetic requirements.

Ecological

- A great variety of microhabitats must be distributed evenly over the surface area of the pattern, allowing all reef inhabitants to compete in an equal matter.
- Pits in varying sizes, equally distributed.
- Focus of vertical crevices on the top half.
- Focus of horizontal continuous crevices in the middle of the pattern.
- Focus of horizontal intermittent crevices on the bottom half.
- Focus of smoother surface textures (eroded, like fossilized coral) on the top half.
- Focus of rougher surface textures (representative of living coral) on the bottom half.
- The applied surface texture for habitat builder larvae is most present at depths of 10-20mm (-20 ≤ x ≤ -10 mm).
- The pattern provides refuge for mobile habitat regulators at depths of 5-50mm.

Production

- Every 1cm in depth of a design element must be accompanied with at least 1cm in width.
- The deepest crevices have depths of 0-30mm. (-30 ≤ x ≤ 0 mm)
- The form liner has no inward undercuts or overhangs.
- All edges and corners are rounded for smooth transitions.
- A depth of 0mm is equally distributed over the pattern surface area, for stability when stack ıg.
- The pattern design must fit the dimensions designated area on the ReefBlock.
- The same pattern can be applied to all sides (long and short) of the ReefBlock.

Stakeholders

- The pattern takes into account the tunnel shapes in the ReefBlock.
- The pattern has the Reefy logo incorporated.
- The pattern visually represents a lobed brain coral.
- The pattern is perceived as aesthetically pleasing by the general public.

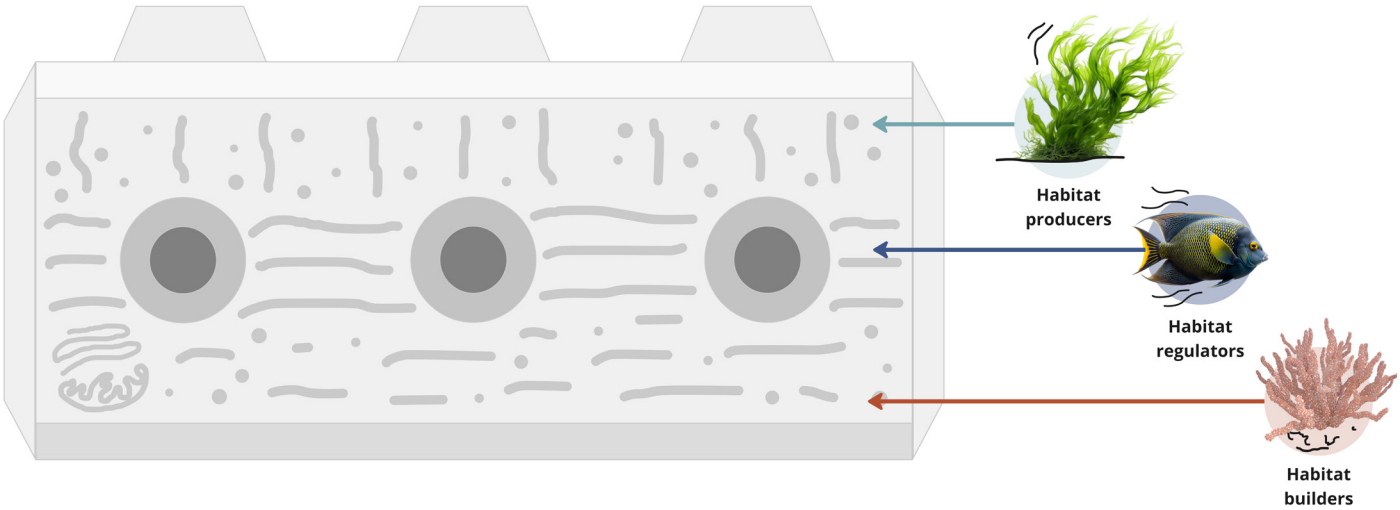


Figure 34: *Ecological and easthetic requirements visualized on the ReefBlock.*

4

Design vision

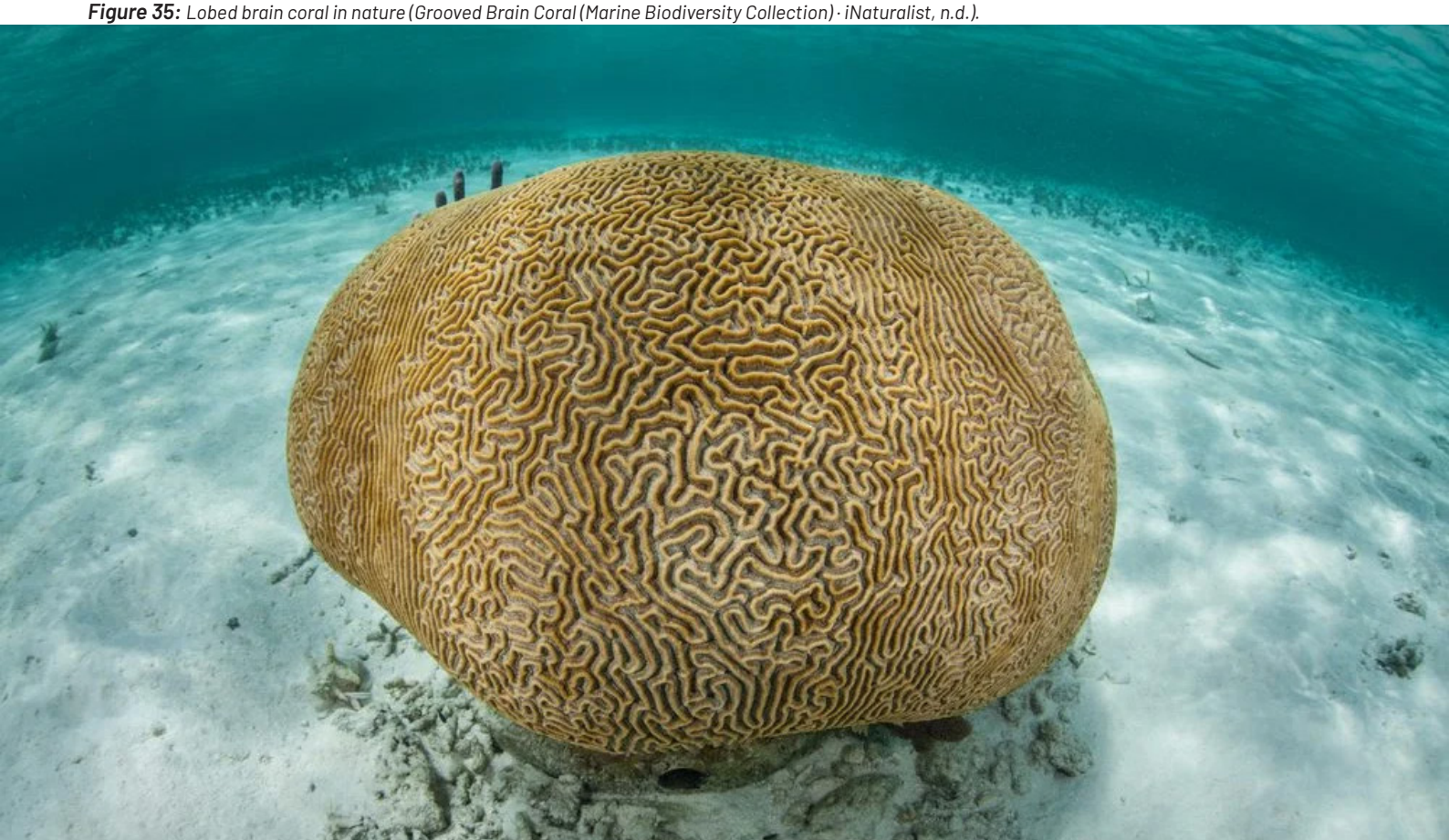
This section discusses my design process towards defining a design vision for the final pattern design. Different methods using different media were tried, in order to understand what design direction would have the most potential for:

- The flexibility for the overall look and feel of the;
- The opportunity for creating a great variation of design options during my development phase;
- The ability to implement the necessary design features in different orientations;
- The effect of shadow created by the (different) design features.

Finally, it was decided that the representation of a lobed brain coral showed the most potential for all four criteria (Figure 35).

It was expected that this design direction allowed for the creation of the most versatile patterns during the ideation phase, as well as the natural incorporation of the Reefy logo.

Figure 35: *Lobed brain coral in nature (Grooved Brain Coral (Marine Biodiversity Collection) · iNaturalist, n.d.).*



4.1 | Initial exploration

In theory, the proposed pattern could be any 2D image that is translated into a 3D surface design that meets all the requirements as concluded from the literature research (Chapter 3). It is clear that the use of design features such as crevices and pits of varying sizes and directions is important for facilitating the formation of reef structures and communities. Naturally, mimicking the geogenic or biogenic hard substrates that habitat builders attach to, both in function and visual representation, is a great starting point.

On the other hand, the rectangular shape of the Reef-Blocks inevitably stands out against the marine environment they are placed in. Therefore, it is also an interesting direction to embrace the fact that the artificial reef structure is human-made and make it into some form of art with relation to a marine context (Figure 36). This 'work of art' could have different purposes:

- Allowing for artistic freedom in the form of modern art or recreating, for example, Ancient Greek art to hint towards a miniature Atlantis.
- So-called '**flagship marine species**' can be used that generally represent (the conservation) of marine life, such as corals, shellfish (or ammonite) or turtles in a more literal illustration.
- The use of a distinctive repeating pattern or geometrical shapes, such as so-called Voronoi patterns, that are commonly used in architecture and parametric design.
- Branding purposes, like the logo or company name on top of or incorporated into the pattern design.

Within the design direction of biomimicry, I distinguished the geogenic substrate properties of a rock surface, and the biogenic substrate properties of different habitat builders (Figure 36).

- 'Branching' flagship species representative for reef restoration efforts and a marine context in general are, for example, staghorn corals and large seaweeds that can have overlapping, multi-layered elements.
- Brain corals are also a flagship species for coral reefs, and often have distinctive patterns in both 3D and 2D with their lines layout.
- Important habitat builders like bivalves such as mussels and oysters: that are often clustered organisms, creating overhangs and crevices in between them.

The Artificial Intelligence tool Adobe Firefly helped me to visualize the different design directions with different surface structures and textures (Figure 36), in a much faster way and far before I even had digital or physical 3D models. Using this method allowed me to identify the different design directions that resonated with me most, in order to determine my vision for the pattern.

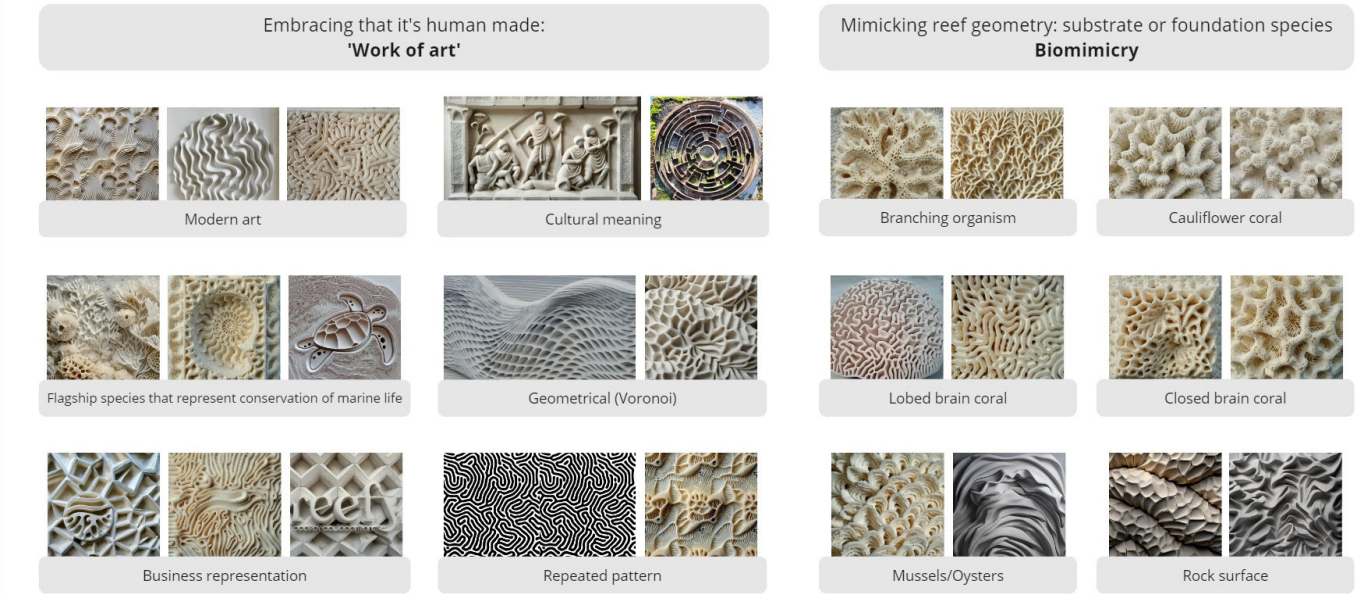


Figure 36: *Generated images using Adobe Firefly.*

Together with Reefy, it was decided to go for the biomimetic design direction, that is a representation of natural reef geometries rather than an art piece, because art is more likely prone to subjective personal preferences. As the aesthetics must be liked by "all", a representation of a natural phenomenon that fits the marine context is more 'neutral' to be liked by the majority of people in that sense.

To further define my design vision for the pattern design, I generated about 70 quick sketches for the surface structure, based on a biomimicry analysis of the shapes and line layouts found in nature (Figure 37).

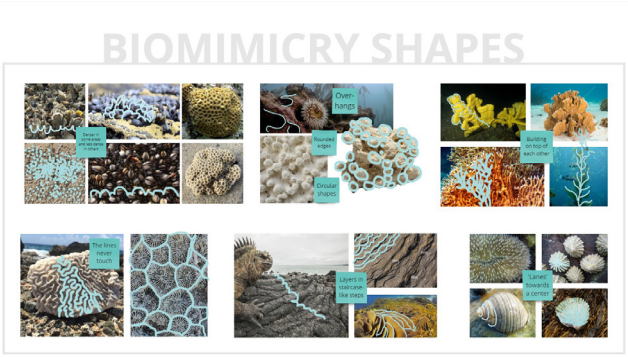


Figure 37: *Analysis of biomimicry shapes and substrate properties.*

The following five directions within the biomimicry direction were used for the sketches (Figure 38, see clockwise).

1. Bivalve reefs;
2. Rock surfaces;
3. Branching corals
4. Hemospherical lobed brain corals;
5. And hemospherical closed brain corals

For each of the directions, I started close to the resemblance and made the design more and more abstract from there, and with different design directions.

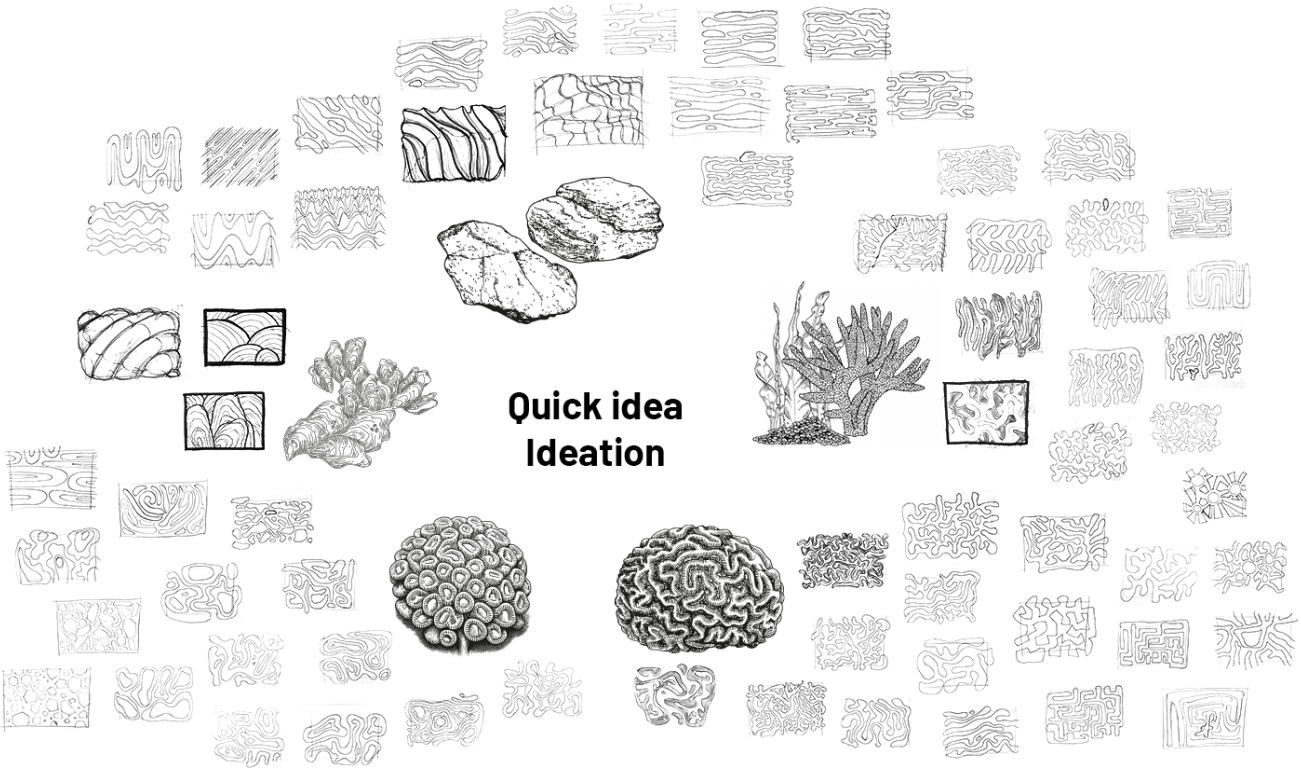


Figure 38: *Initial idea generation in the five directions: rock surface, branching organism, lobed and closed brain corals and bivalves.*



Figure 39: *Physical design explorations based on a few of the initial idea sketches.*

Following the initial generation of images, I transitioned to physical prototypes by creating designs out of clay for each of the biomimicry directions (Figure 39). This hands-on activity provided a tactile experience, enabling me to see how different features interacted with each other regarding shadow and functionality. It helped me to further understand the aesthetics and dimensions in a physical 3D structure. For each of the biomimicry substrates, I created one or multiple clay prototypes, based on sketches that visually inspired me. For the selection of sketches, I chose the ones that were a close resemblance to the different substrates.

In order to better understand what such designs may look like on a larger scale, I visualized a selection of the prototypes in a repeating pattern on an illustrated ReefBlock and evaluated the designs for:

1. Their overall look and feel;
2. The opportunity for creating a great variation of design options during my development phase;
3. The ability to implement the necessary design features in different orientations;
4. The effect of shadow created by the (different) design features.

For this selection, I chose designs that resonated with me visually and that I thought were a good representation of the biomimicry direction (Figure 40).

The most important insights I learned from the prototypes and design evaluations are about the balance between visual complexity and functionality. While random shapes and varying thicknesses of lines create diverse patterns, shadows, and light zones, too many separate or overlapping elements can make the design appear busy and chaotic, which both Reefy and I did not prefer. The use of closed lines (like the closed brain coral) and overlapping elements (like the branching coral) introduces depth and allows for the creation of pits and crevices of varying lengths and widths, but can also make the design visually monotonous as it offers limited the variety of distinctive patterns. Reefy particularly appreciated the reference to corals, with the carved lines and pits resembling fossilized coral and offering both visual appeal and a great business representation.

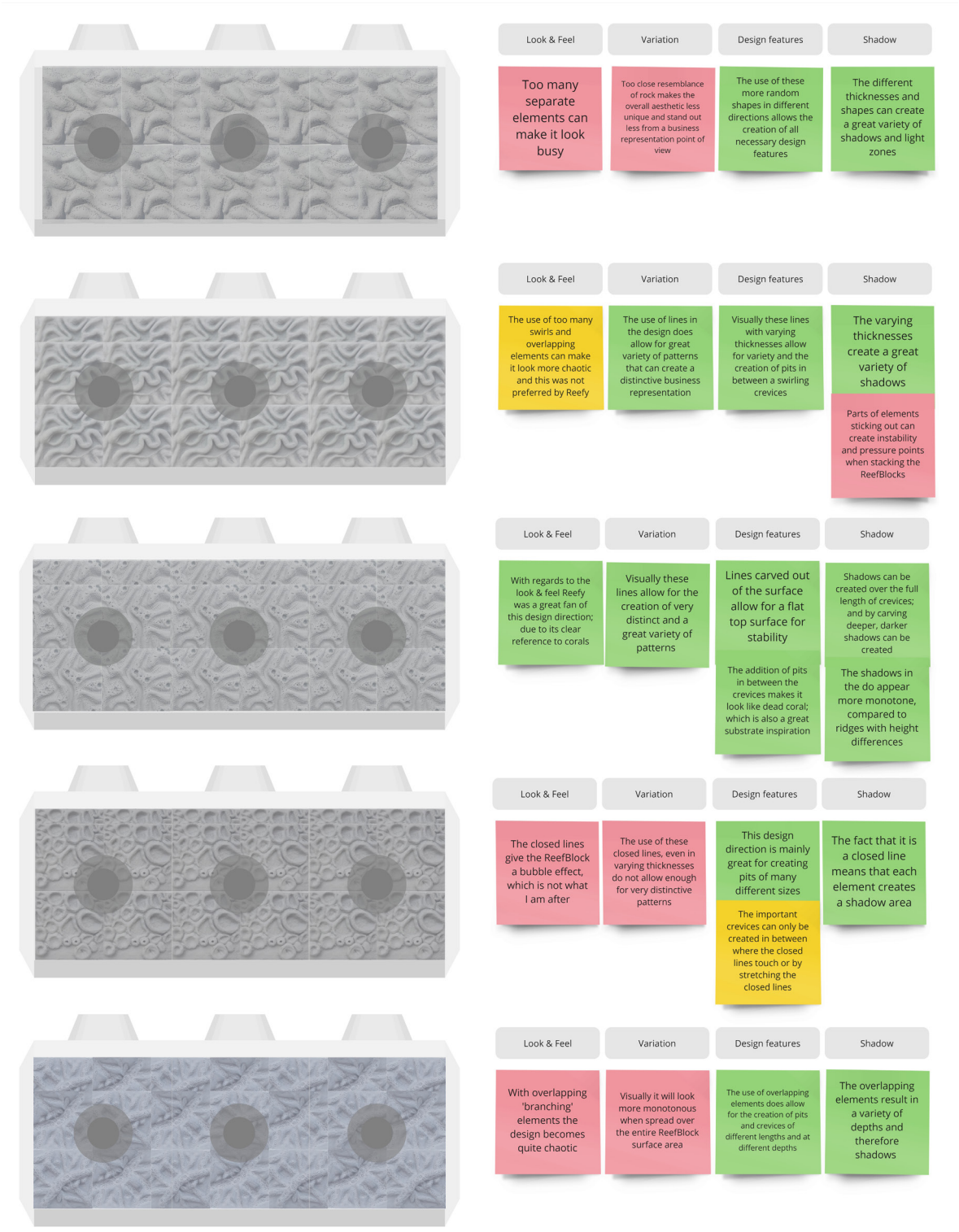


Figure 40: *Physical prototypes visualized on ReefBlock scale, and evaluated by defined criteria for the most potential design direction.*

Designs that have varying heights rather than varying depths create an unstable structure when stacking the ReefBlocks in configuration, as the random heights can create localized pressure points. Thus, balancing visual uniqueness with functional stability is what I deemed essential for the pattern design.

4.2 | Brain coral inspiration

The preliminary form study allowed me to communicate the different directions with stakeholders to determine the design vision for the pattern design. Observing the way the lobed brain corals form looping and swirling line layouts, these natural patterns have an organic complexity that I aimed to replicate in my surface pattern design (Figure 41). Not only for their visual aesthetic, but more importantly, for their functional purpose to serve the different types of marine life. As these lines allow for the creation of the important crevices of different lengths and the natural emergence of pits in the design.

By utilizing the 'line layout' of lobed brain corals, crevices are naturally occurring and pits can be created by an interrupted line or by creating a valley (or depression) in between a curled line.

Even more, similar organic patterns are commonly found in nature and may effectively help to distract from the rectangular shape of the ReefBlocks. This design direction also allows the creation of the most versatile patterns, as well as the natural incorporation of the Reefy logo. Additionally, for the story of the ReefBlock a coral reference makes a lot of sense for the reef conservation context, as well as that it best fits their branding for "Reefy".

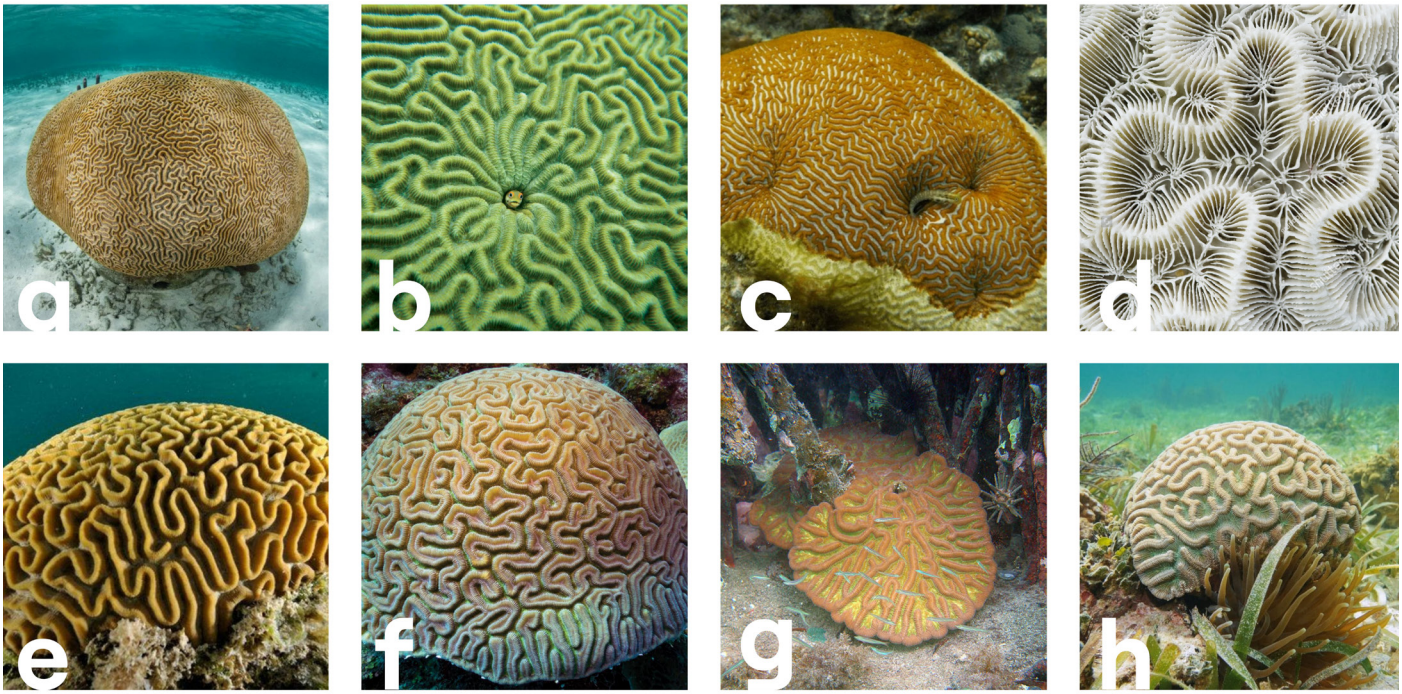


***Figure 41:** Examples of the diverse ways brain corals and their patterns can be shaped. a (Grooved Brain Coral (Marine Biodiversity Collection) · iNaturalist, n.d.); b (The Editors of Encyclopaedia Britannica, 2024); c (Limited, n.d.-a); d (GGZ Archieven - P5COM, n.d.); e (Brain Coral - Alchetron, the Free Social Encyclopedia, 2024); f (How to Identify Grooved Brain Coral, n.d.); g (Colony of Boulder Brain Coral (Colpophyllia Natans) | U.S. Geological Survey, 2009); h (Seadam, n.d.-b).*

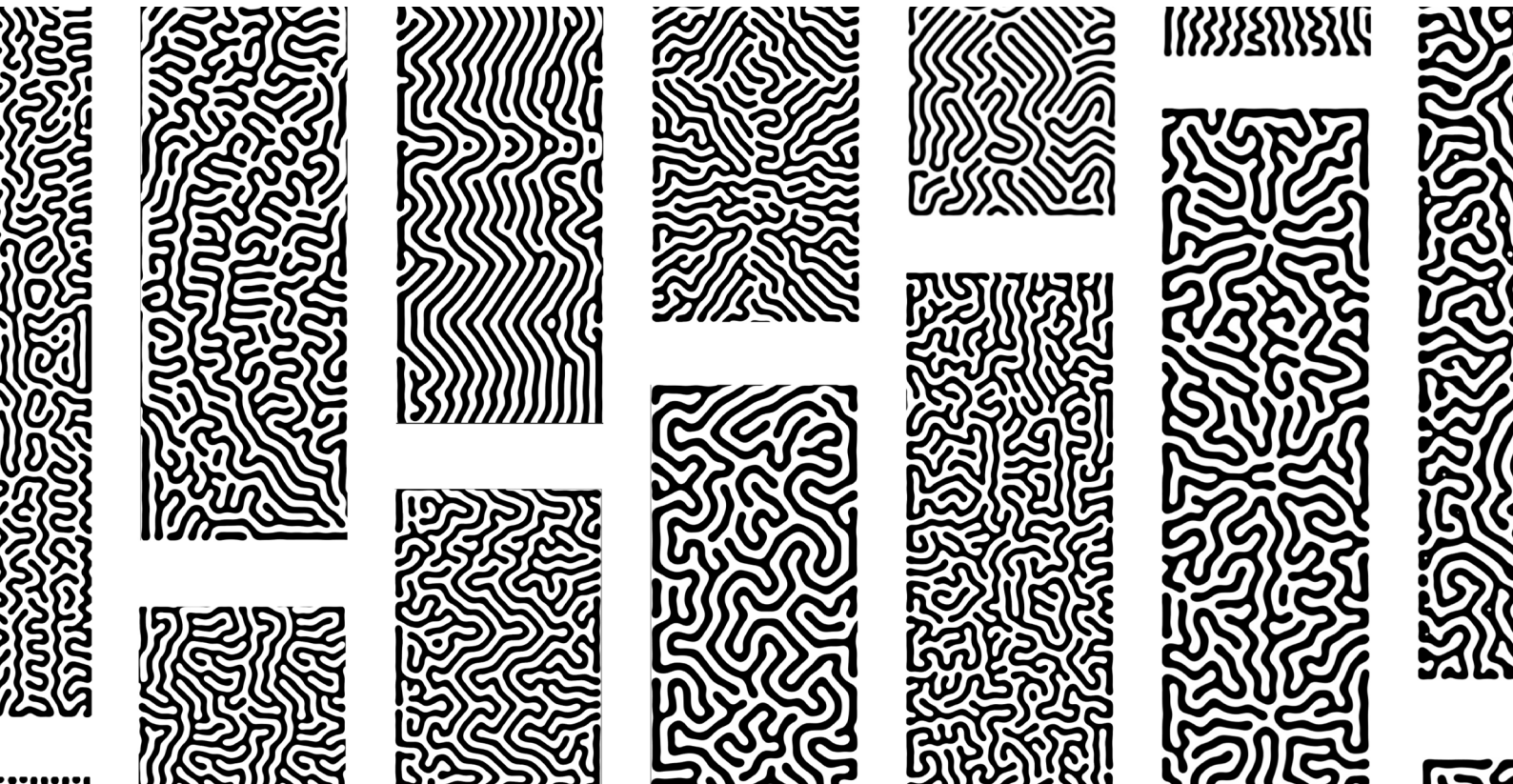
5

Design toolset

For this project two main design tools were selected to help me in the iterative design process:

1. Generative design
2. Parametric design

This section explains what these design tools are, why I used them and how they were used to our benefit in this project.



5.1 | Approach to development

The approach to design my own lobed brain coral pattern evolved a lot throughout this graduation project. For a large part of my form studies, I researched how to implement the lobed brain line layout into one tileable pattern of 400x400mm that could be used for multiple applications. A square tileable pattern has the benefit that it can be seamlessly used as a repeatable wall tile design to enhance quay walls, as this is the direction Reefy wants to extend their product line in. Various techniques were tried to create and compare different tileable pattern designs on ReefBlock scale. Those first patterns were all drawn by hand (both on paper and digitally), which made it a very slow process for iterations from design to digital model. Also, the limited panel size made it more difficult to implement the micro marine spatial planning conclusions (Chapter 3.2) in the intended pattern area. As preferably, the spatial planning is distributed over the entire surface area of the ReefBlock rather than on a smaller, repeated scale.

Fortunately, I found a great method that can semi-automatically generate all kinds of such patterns digitally, including patterns very similar to lobed brain corals, while still being able to have control over the type of design features, their orientation and their size, using so-called generative art. This generative technique aligned perfectly with my project goal to utilize a parametric model and provided me with a new tool to digitally produce organic textures, based on this naturally occurring phenomena. With this combination, I had created a practical and powerful toolset for myself that helped me to create a bunch of pattern proposals and iterations very quickly.

Later in my project, it became clear that the combination of my research conclusions with the practical toolset, which can quickly create a bunch of different patterns for different applications, is an important contribution to the field of artificial reefs and enhancing biodiversity, and specifically, to Reefy. Therefore, in this chapter, I will explain what generative art and parametric design are and how to combine them into a unique and organic pattern design with three-dimensional complexity.

5.2 | Generative art

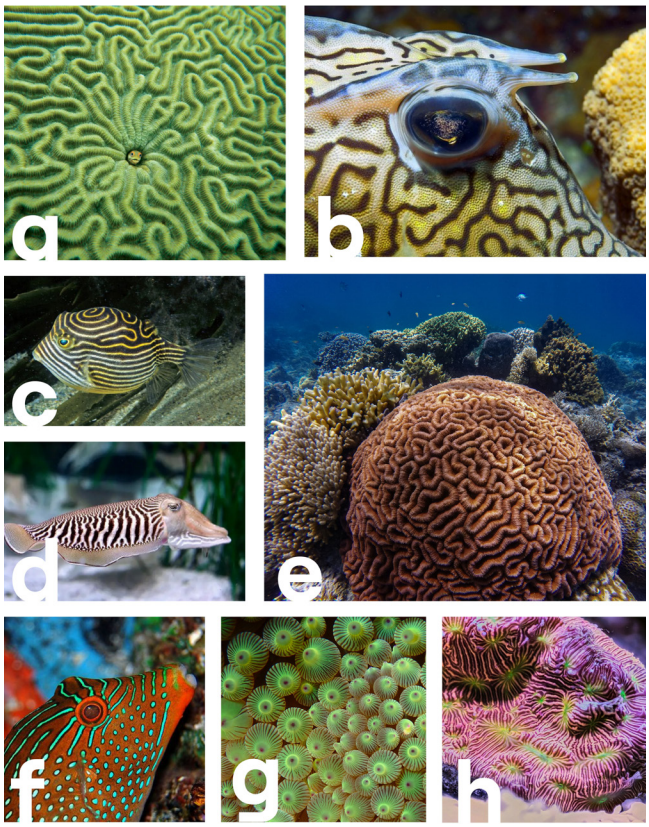


***Figure 42:** Diverse natural examples of reaction-diffusion patterns.* *a (The Editors of Encyclopaedia Britannica, 2024); c (Limited, n.d.-a); b (Dekker, 2012); c (Doosvissen, 2021); d (Natuur, 2021); e (Verheij, 2023); f (Honeycomb Puffer (Canthigaster Janthinoptera) Photos, n.d.); g (Prior, 2024); h (AquaticLog Feed, n.d.).*

Interestingly, lobed brain corals are not the only organisms in nature that display these types of patterns. Apparently, this process is very common in nature and is known as ´reaction-diffusion´. **Reaction-diffusion** systems are responsible for a wide variety of patterns that emerge in natural phenomena. Examples of such patterns range from the intricate patterns found on marine life such as different types of brain corals, fish and many more (Figure 42), to zebra stripes and the ripple patterns in sand, which share very clear similarities in their pattern formation (Figure 43).

To explain the reaction-diffusion system, I will use the sand grain example as an analogy to describe the similar chemical process:



Figure 43: *Comparing sand patterns with the stripes of zebras. a (Mat, 2023); b (Stockfoto Door Wrangel, n.d.).*

'Dynamic' sand grains that are moved around due to the wind or water waves, can be considered as 'reactors' as they meet and interact with static sand grains that resist the interaction and want to remain in place, like 'inhibitors or diffusers'. As reactors encounter inhibitors they will experience resistance or 'inhibition' to the caused reaction, and therefore, reactors will either become diffusers themselves or follow the path of least resistance and be diffused in other directions to further react. Determined by the initial direction of movement of wind or water, the sand will accumulate in some places and be eroded in others, creating distinct, repeating patterns on the surface. This continuous movement and redistribution of sand, leads to the formation of stable ripple patterns, as the system balances out and reaches a sort of equilibrium. That is, until the wind or water moves in a new 'initial' direction. This illustration of the chemical process is similar to how zebras get their striped pattern (see Figure 43 for the similarities).

In 1952 Alan Turing first explained how "natural patterns like stripes and spots can arise autonomously" and that this process of reacting and diffusing can even be mathematically described, which is why such patterns are also sometimes referred to as 'Turing patterns'. Meanwhile, reaction-diffusion patterns have been well researched, allowing the prediction of their final appearance by adjusting a few key variables, which enables control over how the pattern evolves and expands towards a final 'climax' design. As it turns out, such reaction-diffusion patterns can be generated using image editing software (Figure 44).

Generative art is a form of art that is created, at least partially, by an autonomous non-human system. The digital tool takes over action steps that would normally require direct decisions by the designer (Galanter, 2003). Although some aspects of the system can be influenced by the designer, such as the initial parameters or input conditions, the majority of the outcome is produced independently by the system itself.

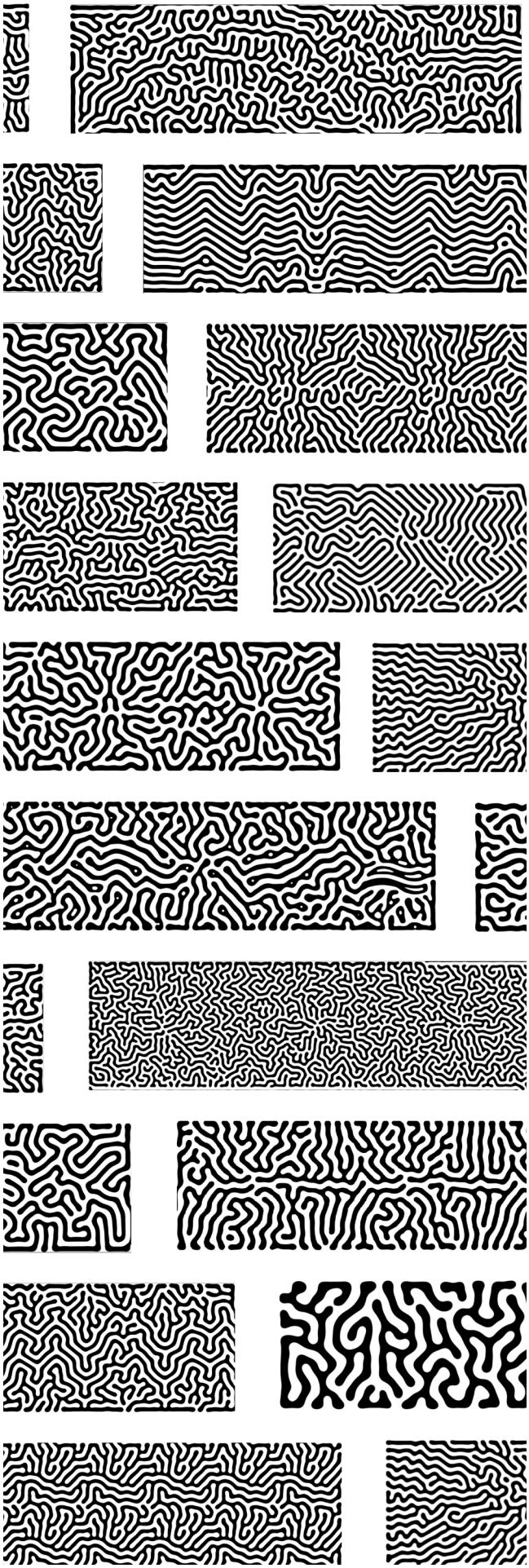


Figure 44: *Various reaction-diffusion patterns created with the generative art tool, throughout my ideation and iteration process.*

5.2.1 | How to achieve generative art

In this report, the exact workings of mathematically defined reaction-diffusion systems will not be discussed. However, these systems can be effectively simulated in image editing software such as Adobe Photoshop. To create a reaction-diffusion pattern, the process requires four key components:

1. an initial image or pattern;
2. a filter that acts as a "reactor" or activator that increases contrast in the image;
3. a filter that "sorts" the pixels to continue as an "activator" or as an "inhibitor"
4. and lastly, a filter that acts as a "diffuser" or inhibitor that spreads the image (or 'pushes' the pixels) across the art board.

The outcome of the reaction-diffusion simulation depends on several factors. One important aspect is the relationship between the size of the artboard (in pixels) compared to the pixel size of the filters applied. This ratio determines how large the final pattern will be, as well as how fast the diffusion spreads across the canvas. Similarly, it influences the number of distinct details that will emerge in the final pattern.

The resulting pattern from the reaction-diffusion process can be influenced by the initial image used in relation to the pixel size ratio: the line width of the element(s) in the initial image, the length and the direction of the element(s), as well as the distance between separate elements, all guide the diffusion and evolution of the pattern towards a specific outcome.

The desired result is achieved by repeatedly applying the reaction, sort and diffusion filters to the initial image (a) in the specific sequence for x amount of times. See Figure 45 for how the reaction- diffusion process allows the pattern to unfold after applying the filters 1x (b), 50x (c), 100x (d), 200x (e) and 300x (f) consecutively.

The interaction between the settings of the filters and the initial image determine what organic designs, typical for reaction-diffusion systems, will unfold. When using the exact same filter settings and initial image, about the exact same result will come out of the system each time.

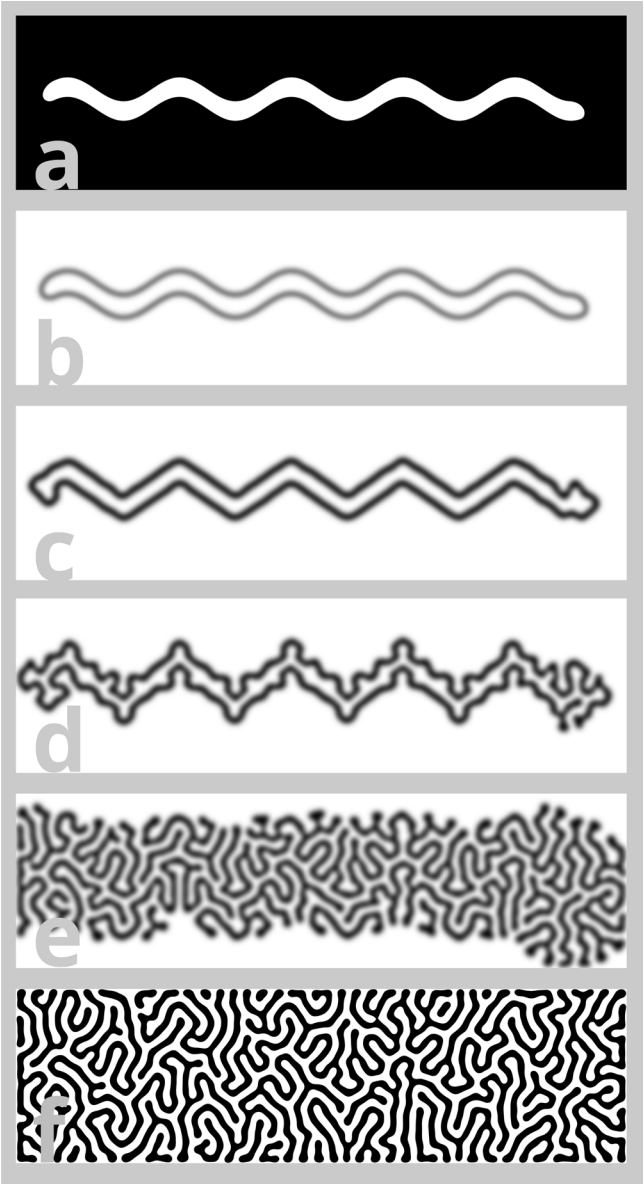


Figure 45: *Step-by-step development of a generated pattern design, from initial image to final 'climax' pattern.*

This way I was able to create a multitude of patterns that are similar, yet with crevices in different directions or pits in varying sizes. And this method significantly reduces the time to iterate the pattern concepts. The most important input for this reaction-diffusion method is an initial black and white image at a specific size, that has specific design elements at specific locations and with a specific dimensions, and the settings at specific pixel sizes, in order to create a final pattern design that meets all the ecological requirements as well as the aesthetic vision for the pattern design on the ReefBlock.

5.3 | Parametric design

A **parametric model** is a powerful tool that can be used to precisely generate and manipulate complex surface structures, which has proven to be crucial for my project designing the pattern design for the ReefBlock form liner. The commercial CAD modeling tool Rhino(ceros) has a built-in tool called Grasshopper, which adds parametric design capabilities. Whereas Grasshopper allows users to build algorithms using code blocks from an extensive library, which generates a model based on variable input parameters. Rhino allows users to view their generated model and, after so-called 'baking' the model, to manually modify it. This setup provided me with the power to quickly manipulate and refine the design by only adjusting the input variables.

5.3.1 | How to achieve a parametric surface pattern in 3D

The process begins with generating a two-dimensional grid of control points, sized to match the dimensions of the Reef Block form liner, and which is the exact size of the pattern area on the ReefBlock: 2800x800mm. This grid forms the foundation with which the complex 3D surface structure can be created and the resolution of the final surface structure is determined by the number of control points in this grid (Figure 46, red grid).

The most important step in the parametric model involves the use of an image sampler, which is a code block that can read the color value of the pixels, and can convert that information into a numerical output. Which means that the retrieved numerical values from the image sampler can be used to move each individual control point in a specific direction with the appropriate distance, specified by the corresponding color value of the pixel in the image. This numerical output can be easily remapped, to meet the requirement that all outputs fall between the depth range of 0-30mm.

The grid of points, now positioned in three-dimensional space and moved only in the z-direction (Figure 46, green point cloud), collectively forms a point cloud that resembles the initial 2D image. A closed 3D surface can be created by connecting all the adjacent control points in the grid (Figure 46, smooth red surface). After adding a thickness, this surface can later be directly used for further production processes (Figure 46, white panel). Essentially, in this model, the pixels in the image are the variable parameters. When a new image is used as input, the surface structure and texture instantly change while keeping all other design steps, allowing for a quick and efficient iterative process of the surface pattern design, immediately digitally rendered in 3D.

In the generated CAD model, a white pixel means that the associated point moves by exactly 0mm, while a black pixel means that the point moves by exactly 30mm in depth. Gray values correspond to depths anywhere between 0 and 30mm, depending on their exact percentage of black. The appearance and surface texture of the pattern design depends heavily on the differences in color between adjacent pixels in the image. If the color difference between adjacent control points is significant, the resulting surface transition will be harsher. However, smoother transitions can be achieved by making use of gray values that make a gradient between black and white across a certain number of pixels/control points, by means of a blur filter. How harsh or how smooth that transition is in the generated surface, again, depends on the pixel size of the applied blur filter.

Concluding, the use of a parametric model is a highly efficient method for generating the complex surface textures required for the Reef Block form liner. This method can be used for digital rendering, physical prototyping and production of the form liner (mother mold). The input for this parametric design method is a black and white image, which can be easily created using the reaction-diffusion method. What is really great about this method, is that the grid of points can never create undercuts or overhangs in a perpendicular direction to the release direction of the mold.

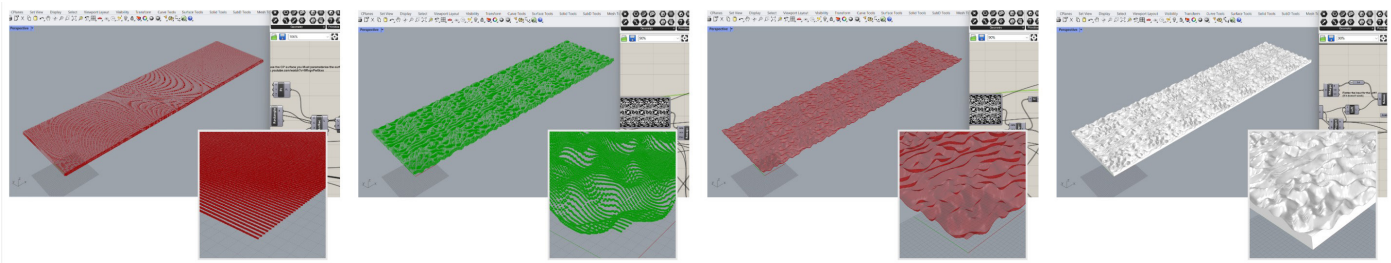


Figure 46: *The automated process steps defined in the parametric model.*



Concepts

This chapter describes the way the design toolset, that combines the power of generative art with the power of parametric design, was used to create the final proposed pattern design. This process was composed of different consecutive steps that needed to be taken within a specific workflow in order to meet all ecological, production and stakeholder requirements.

The workflow combines different steps that each add creative input for a next and aid in achieving the desired design features.

In this section the steps of the workflow are used to generally describe what my design process was towards three proposed concept patterns (Figure 47).

The use of generative art allowed for rapid creation of more and varying designs. And finally, three concepts were proposed to the general public in the form of a survey.

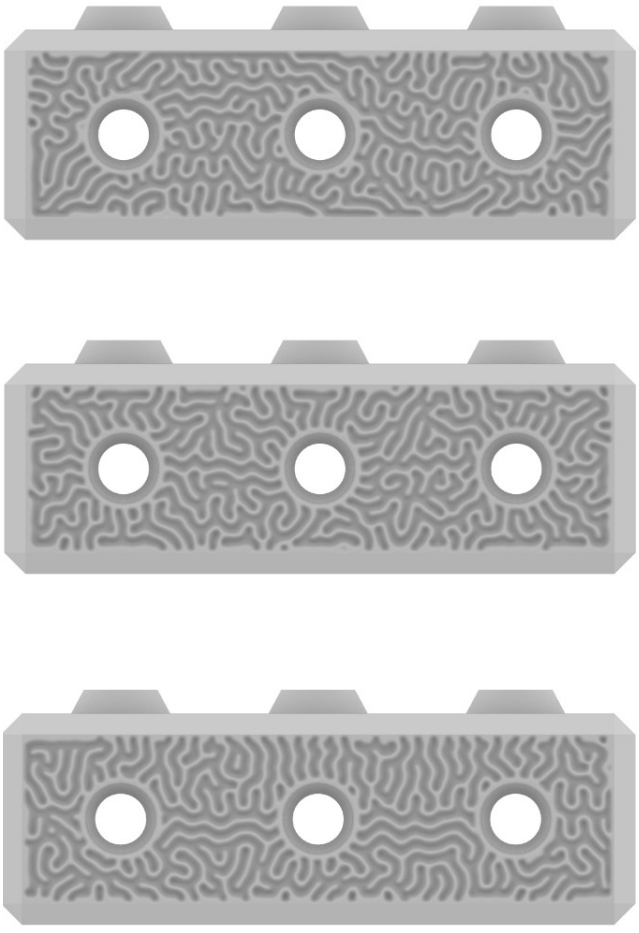


Figure 47: *The three proposed concepts that were used in a survey to understand the general public's view on the overall aesthetics.*

6.1 | Work flow

This section describes the workflow for creating the pattern design, using the design toolset I composed as explained in Chapter 5. Following the workflow illustrated below in Figure 48, the different process steps from the input of an 'initial 2D image' until a designed 3D modelled surface, that meet all spatial planning requirements (as concluded in Chapter 3), on both centimeter- and millimeter-scale.

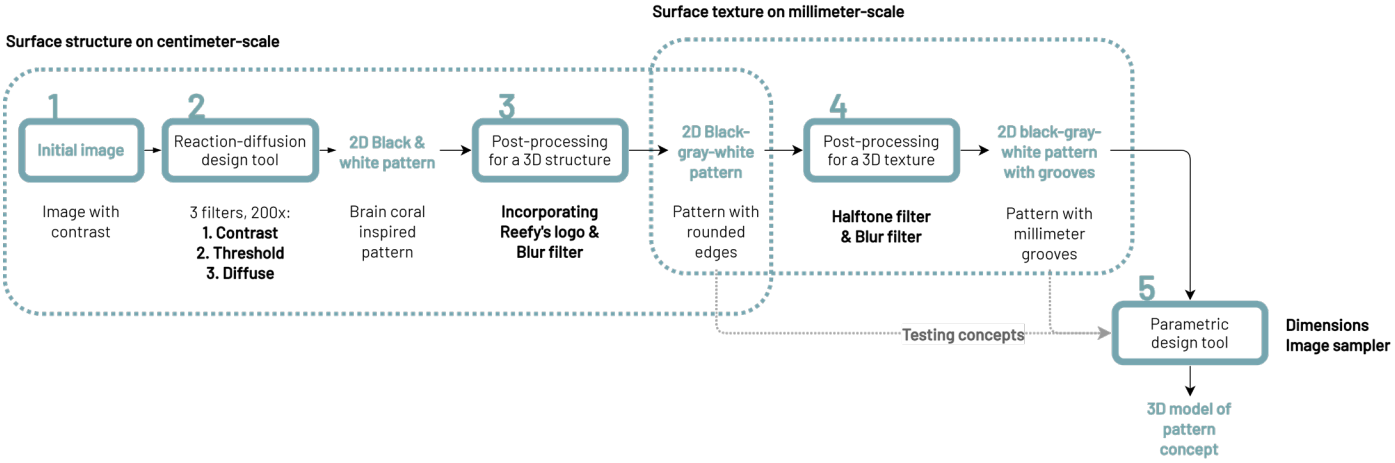


Figure 48: *The developed workflow with the design toolset using steps from the generative art tool up to the parametric tool.*

As described in Chapter 5, we need a black and white image (with gray values) that is directly translated to create the complex 3D surface with the parametric design tool. And the reaction-diffusion tool was chosen to generate the black and white image necessary for achieving the desired meso-micro spatial planning in that 3D surface.

The workflow exists of multiple steps to create that input image for the parametric model, using one image editing software, like Adobe Photoshop, used in this project (Figure 48):

1. The initial image must also be a contrasted black and white image, before using it in the generative art tool. This initial image determines where and what design elements will be present in the pattern.
2. A 2D black and white pattern comes directly out of the generative art tool and makes sure that all the desired desired design features are present.
3. Post-processing steps with the generated pattern can make sure that additional aesthetic, ecological and stakeholder requirements are met. And the output of these steps is a new 2D black-gray-white image which can already be used as the input for the parametric model, without added texture.
4. Post-processing steps with the 2D black-gray-white image can make sure that the pattern design also meets the requirements at millimeter-scale. For the final pattern design this created image was used as the input for the parametric model.
5. The parametric model allows you to change the image, with no further design steps that need to be taken in this tool. Which showcases the power of parametric design in a iterative process.

By using an art canvas size of 2800x800 pixels, each individual pixel from the 2D image can be translated one-on-one to the displacement of the individual control points, to create the desired 3D surface.

6.2 | Surface structure on centimeter-scale

First, it was a priority to thoroughly understand the specific settings that are needed to achieve the desired pattern design with the correct dimensions (line width of on average 30mm), how the different settings interact with each other and the initial image used. With a clear vision in mind, I systematically explored and adjusted these settings to carefully guide the image toward the intended look and feel. This systematic approach allowed me to gather insights about using the tool, while simultaneously exploring different concepts for

the final pattern design. Making this process extremely fast and efficient.

Insights: Black & white image smoothed

By means of the generative art tool you easily create hundreds of concepts that are all almost readily applicable in the parametric design tool. The reaction-diffusion method often creates line segments, leading to crevices when translated into 3D. Dots in the 2D image, when subjected to the right settings, result in pits in the 3D design.

- Elements added to the initial image and placed close together remain more visible in the final pattern, since they quickly achieve equilibrium. This effect can be controlled by adjusting the line width of the design elements to match the final pattern's line width (Figure 49).
- Also, the orientation and spacing of design elements affect how the pattern evolves between them, with more iterations causing elements to blend and smooth out over time, reaching equilibrium when the canvas is fully covered (Figure 49).
- The blur filter in the reaction-diffusion tool controls the line width of the final pattern, which influences both the size of the elements and the speed at which the canvas fills. A larger blur results in wider lines (Figure 50).
- The contrast filter, on the other hand, determines how many distinct elements appear in the final design. Unintuitively, the lower the contrast filter value, the more distinct elements will be generated (Figure 51).
- Larger line widths in the initial image lead to more swirling patterns, while blank spaces tend to fill with linear elements (Figure 52).

Finally, to create crevices approximately 30mm wide, a blur filter of 12px and a contrast filter of 6px worked best for a 2800x800 pixel canvas. And with the element line thickness in the initial image close to the final line width in the generated pattern, to better control the outcome and resulting in a pattern suitable for the ReefBlock (Figure 53).



Figure 53: *Example reaction-diffusion pattern with the blur filter of 12px and a contrast filter of 6px.*

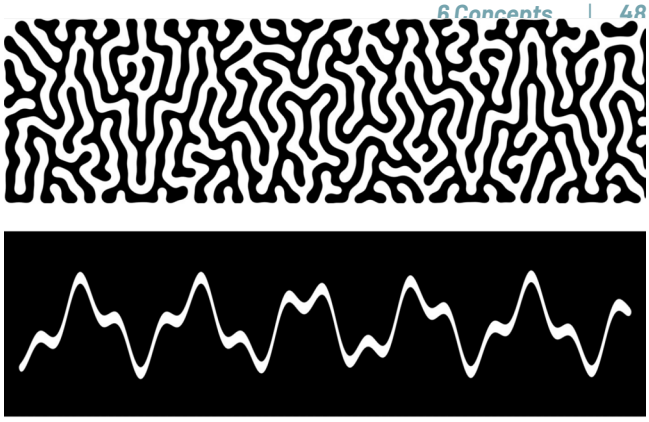


Figure 49: *Comparing the final image to the intial input image.*

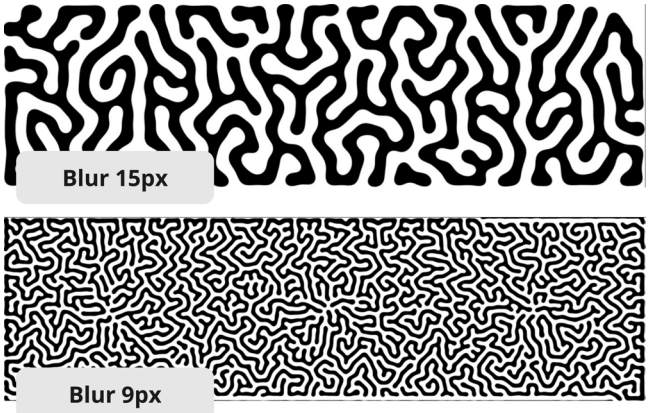


Figure 50: *Comparison of setting different blur filter pixel sizes.*

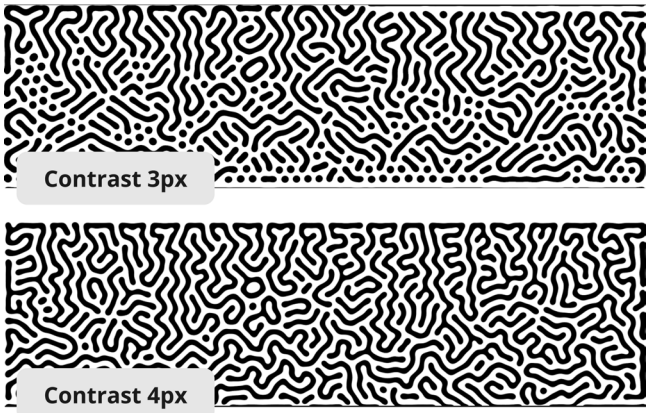


Figure 51: *Comparison of setting different contrast filter pixel sizes.*

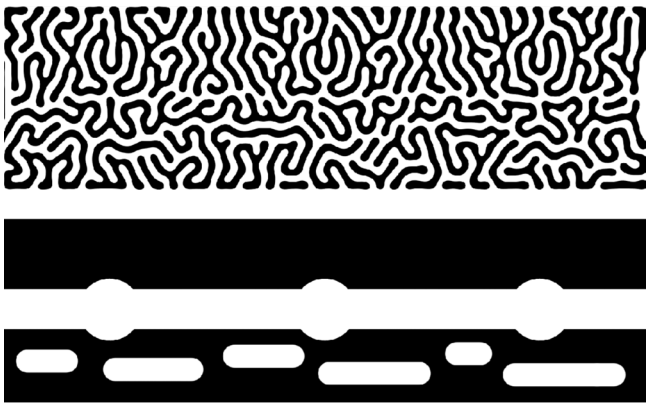


Figure 52: *Comparing the use of lines more in proximity at the bottom, a thick line in the middle and empty space up top, with the outcome.*

Post-processing for the 3D surface structure

Post-processing the 2D image was necessary to achieve the desired transitions in the 3D surface. Through experimentation, I found that using a blur filter was essential for smoothing the surface finish Figure 55. A larger blur creates more gray pixels, leading to softer gradients between black and white. Within the parametric tool it is possible to switch if black or white in the image means a depth of 30mm or 0mm. This allows to either have the generated pattern to be a protrusion or a recess in the structure (Figure 54), option b is actually better resembling the physical depth structure of lobed brain corals.

Additional insights from post-processing steps to create the desired 3D surface structure are:

- Blurring the final image ensures that the crevices meet production requirements, such as maintaining a crevice width equal to or wider than its depth, preventing weak spots in the form liner. A final blur of 8px, applied after sharpening, provided the desired surface transitions for the 3D structure (Figure 55a). This blur distributed the color values evenly, ensuring a smooth surface structure compared to when you don't (Figure 55b).
- The ratio between white and black lines, influenced by the blur filter in step 2, also affects the sizes of crevices and pits in the 3D model. After generating the image, applying a sharpening filter helped reveal the pattern's details and adjust the line weight of the black lines (Figure 56).
- Incorporating additional pits and the Reefy logo into the pattern design were also important steps. This was achieved through multiple post-processing steps using the image editing tool (Figure 57).

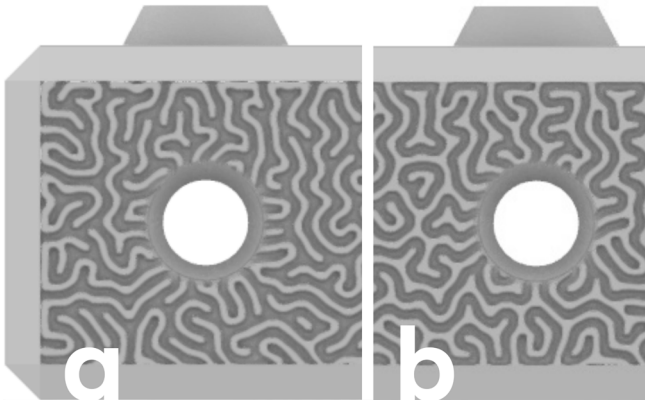


Figure 54: *Comparing when a) black is depth=0mm & white is depth= 30mm, to when b) white is depth=0mm & black is depth= 30mm.*

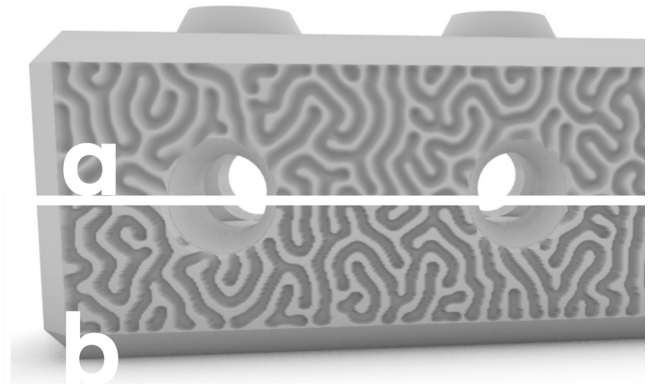


Figure 55: *Comparison blurred final image versus non-blurred.*

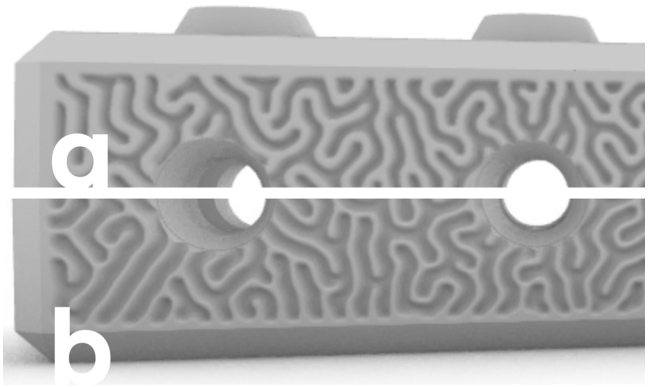


Figure 56: *Comparison line input image thickness and resulting surface.*

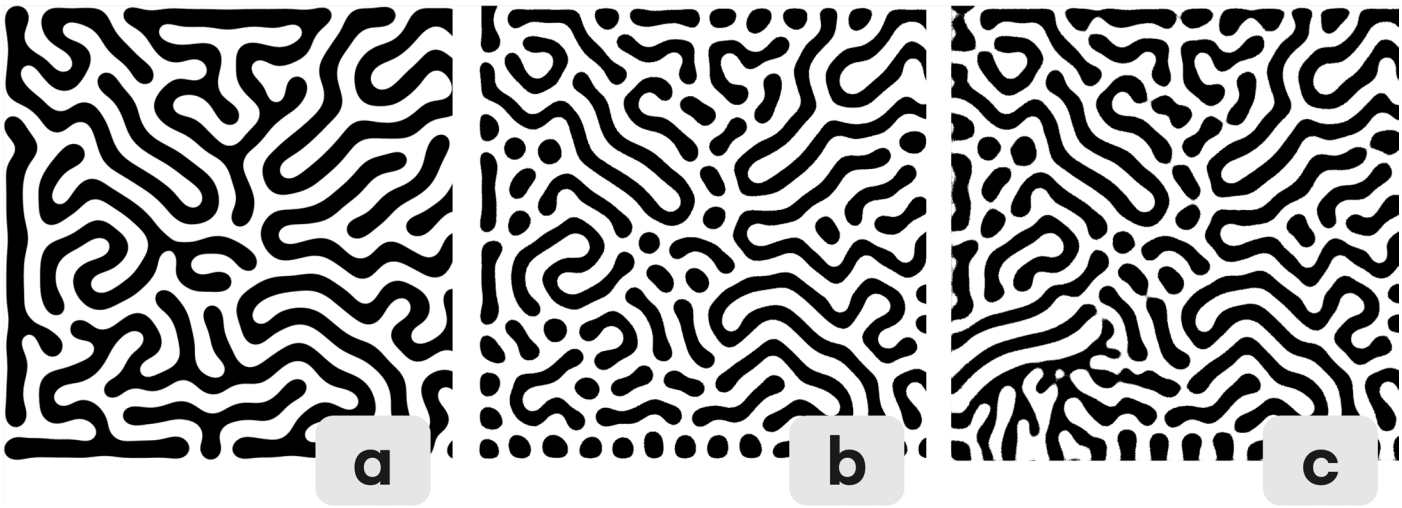


Figure 57: *The post-processing steps a) generated reaction-diffusion pattern, b) Additional round of reaction-diffusion to create the desired pits, and c) the slow multi-step process to oncorporate the Refy logo seemlessly.*

6.3 | Surface texture on millimeter-scale

Once the 2D image for the pattern structure is ready, it is important to further modify the image to create a surface texture on the millimeter scale. As discussed earlier, surface textures with small grooves are crucial for the settlement of habitat-building larvae. The challenge was to achieve these textures while preserving the overall look and feel of the pattern.

Insights: Black & white image grooved

Various filters were explored for the 2D image and their effects on the surface texture (Figure 58). It was clear that, again, the use of a blur is essential to avoid any weird sharp textures in the model (b & c), but not too much, as all applied texture will disappear again (d).

Post-processing for the 3D surface texture

Based on research, the final design aimed for grooves that encourage larval settlement. A halftone line effect was determined to create the most functional and visually appealing texture (Figure 58a).

- The gradient of gray values in the 2D pattern, resulting from the blur in the output image (Figure 59a), was used for the halftone effect that creates "3D printed layers" or grooves that provide the necessary grooves for larval settlement (Figure 1b).
- Applying the halftone effect along the contours of the structure ensured that these grooves aligned with the natural curves of the pattern, particularly in areas where the surface transitions into deeper crevices (Figure 60).
- Since 1px in the 2D image corresponds to 1mm in the 3D model, the halftone effect was set to 1px, with an additional blur of 8px to create softer ribs for a more natural texture (Figure 61).

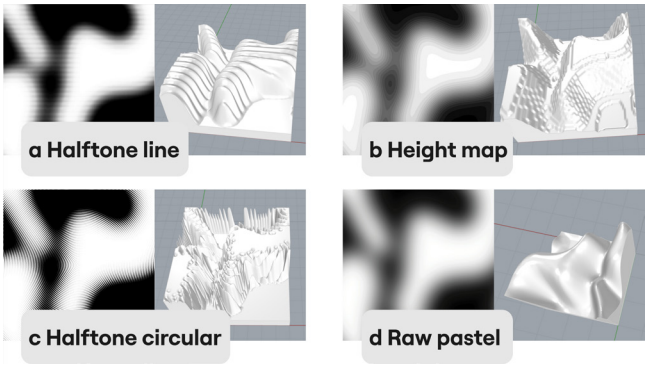


Figure 58: *Examples of different surface textures in Rhinoceros Grasshopper.*

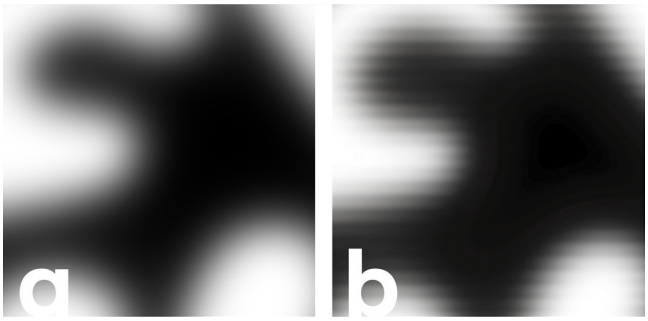


Figure 59: *From a) output image from the reaction-diffusion tool to b) post-processing with halftone effect and additional small blur.*

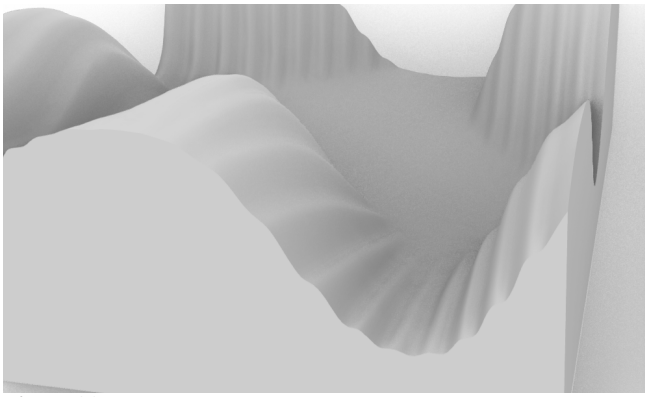


Figure 60: *Close-up of the applied grooved surface texture.*

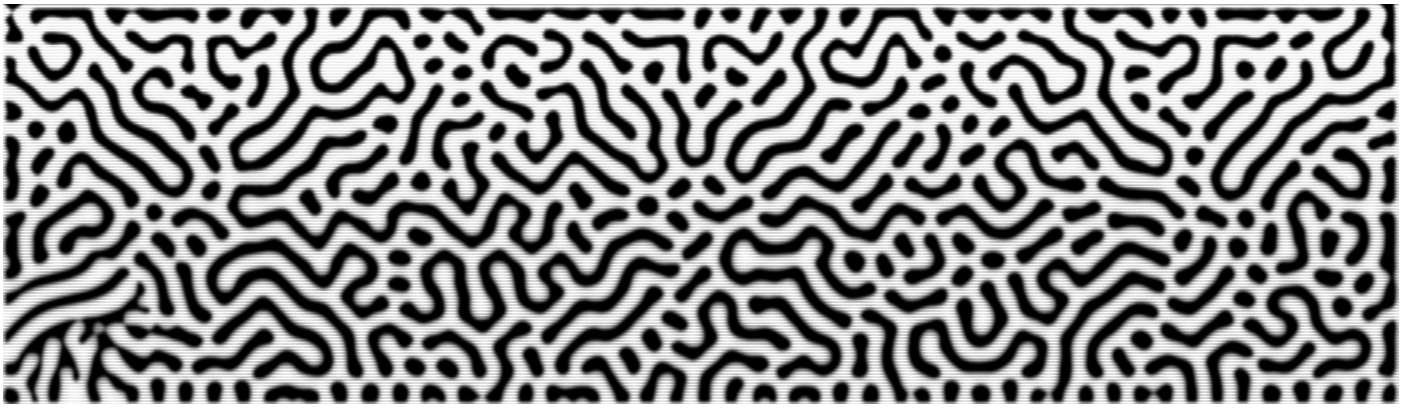


Figure 61: *Halftone effect applied on the full-size of the ReefBlock.*

6.4 | Pattern design concepts

Now that we have generated the 2D black-gray-white images that have gone through the necessary post-processing steps for creating the desrired design features on both centimeter and millimeter scale, we can explore what they look like in the parametric design tool on the scale of an entire ReefBlock.

To determine which lobed brain coral-inspired patterns worked best on the ReefBlock, I created a complete rendering model in Grasshopper. This model rendered the pattern on all five sides of the ReefBlock, providing an immediate understanding of the design's aesthetics on a full-size scale (Figure 62).

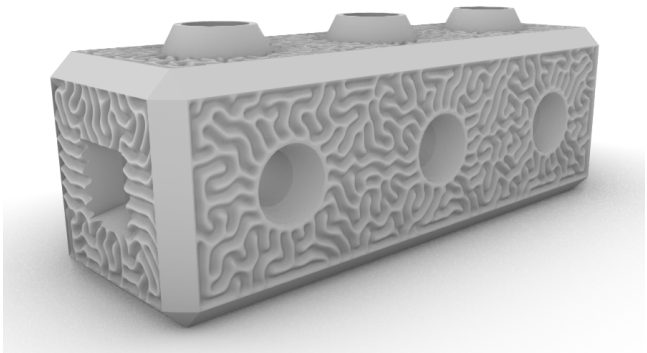


Figure 62: *The complete ReefBlock for quick visualisations.*

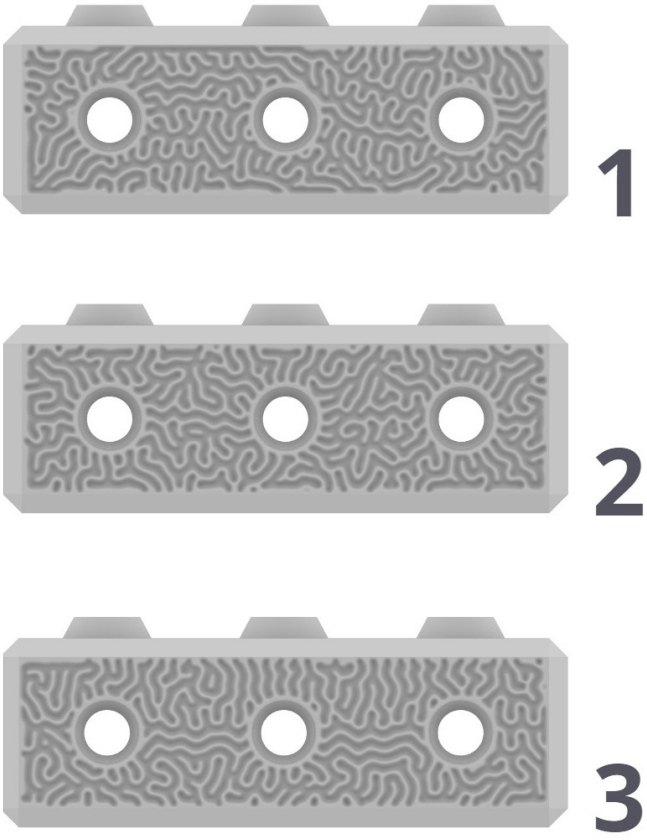


Figure 63: *Three proposed concept patterns, with 1) interacting across the surface; 2) concentrated around the holes; 3) literal representation of the spatial planning features.*

Throughout the trials, I explored three main design directions:

1. Patterns that interacted across the entire surface of the ReefBlock.
2. Designs concentrated around the holes in the ReefBlock.
3. Patterns that used the spatial planning features as input, creating clear sections.

The proposed concept designs were based on what I thought were the best representatives for the different pattern directions. All three concepts (Figure 47) were designed to meet the most important requirements for the final design, with regard to the ecological, production and stakeholder requirements.

Ecological requirements

All concepts that are created using the design toolset are able to meet the ecological requirement for grooves at millimeter-scale, by means of applying the post-processing step. Additionally, the generative art tool allowed for the control over the required design features for the reef inhabitants in the generated resulting pattern.

- **Grooves** of 1-3mm in width and depth that are dominantly applied between depths of 10-20mm
- **Crevices** of average 30mm in width and depth
- **Vertical** oriented crevices at the top
- **Long horizontal** oriented crevices in the middle
- **Shorter** oriented horizontal crevices at the bottom

Distribution of varying sizes of pits was not yet implemented, as this is part of the post-processing steps for the final proposed design

Production requirements

By means of the design toolset, it is inherently ensured that all production requirements are always met regarding:

- **Draft angle & 1:1 width-depth ratio**: the applied blur in post-processing creates both smooth transitions, slight draft angles and ensures that any thin crevices will be blurred to a lighter gray value that equal shallower crevices.
- **Avoidance of overhangs and undercuts**: the use of the tool to create the 3D surface (by means of moving a point cloud only in the relative 'z-direction') can never result in overhangs or undercuts.
- **Depths of max. 30mm**: are secured within the design parameters of the parametric model.

Stakeholder requirements

At the basis of the generative art tool is that it simulates the natural process found in brain corals and other natural examples as described in Chapter 4. Therefore, all pattern concepts inherently take on a form that closely resembles the lobed brain coral that was envisioned. For each concept, the goal was to make the pattern look integrated with the ReefBlock, rather than merely applied to it. However, in order to determine what design direction would be the most interesting for Reefy to use for the final proposed pattern design, a short online survey was distributed to collect general opinions.

The selection of the best pattern design that is proposed was based on the clarity and distinctiveness of its features in comparison to other designs and the way it integrated seamlessly with the ReefBlock as a whole.

6.4.1 | Aesthetics survey

In order to understand the aesthetics preferences of the general public, a survey was distributed amongst engineers with different backgrounds, as well as marine biologists and also people outside those demographics, including a range of ages. The used form for the survey and the complete set of results can be found in Appendix D.

The three final proposed concept designs (Figure 47) were compared, based on six statements, by means of a Google Form. Correspondents had to choose the pattern that fit the statement best, for each of the six statements:

1. This pattern is visually most attractive to me
2. This pattern reminds me of a brain coral the most
3. This pattern visually looks like it was designed specifically for the ReefBlocks the most
4. This pattern has the most balanced design
5. This pattern I think best fits a marine context
6. This pattern helps 'break' the rectangular shape of the ReefBlock the best

These statements were aimed at collecting the general opinion on three categories that are important for people to understand and agree with. For each category, two questions were aimed to understand the average general opinion.

The overall aesthetic was surveyed by questions 1 and 4; The design vision in context was surveyed by questions 2 and 5; and the integration of the pattern with the ReefBlock was surveyed by questions 3 and 6. All statements were formulated in the positive sense, to avoid mistakes by participants.

The designs were shown without any of the post-processing steps, in order to collect the general public's opinion on the overall aesthetics of the pattern only and to make sure that the specific post-processing results, that are based on both the stakeholder, production and ecological requirements, do not influence their judgment.

The survey was meant to be as short as possible and all information and questions were displayed on a single page (Figure 64) in order to decrease the friction to fill in the survey as much as possible, and also to let people know what they can expect to avoid them from stopping to filling it in halfway, for example.

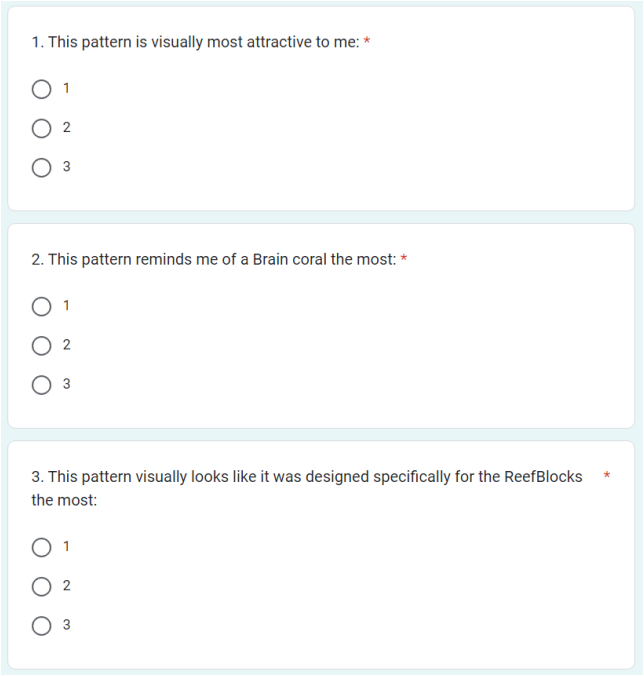


Figure 64: *Three example questions in the survey.*

Additional information was provided about what artificial reefs are, what a ReefBlock is in context and where the pattern design will be implemented, to help participants understand the context of the project. And examples of different brain corals were presented, in order to provide the participants with a comparison.

Collected insights

The results of this survey were not further analyzed than the results showing in the Google Form, as this was a very short and subjective survey. However, from the survey the following main conclusions were clear:

- 39% of the respondents had prior experience with seing a natural reef in real life, and 61% did not, which I thought was relatively high and may have help the respondents to envision the structure underwater.
- Most interestingly, for questions 1 and 4 (both the general aesthetics questions) pattern 2 was a clear winner (Figure 65).
- For questions 2, 3 and 6 the general opinion was divided mainly over pattern 2 and pattern 1.
- A seemlingly more dividing question was question 5 about which design fits a marine context best; perhaps this questions can be interpreted in very diverse ways.
- Although, pattern 1 reminded respondents of a brain coral the most; perhaps due to the fact that this design does not interact as much with the ReefBlock holes.
- The average age of the respondents was about 28.

In conclusion, from this survey it was clear that pattern 2 on average scored best for most of the statements, which is why it was decided to go prepare that design direction for the final proposed pattern, using the work-flow as described in this chapter.

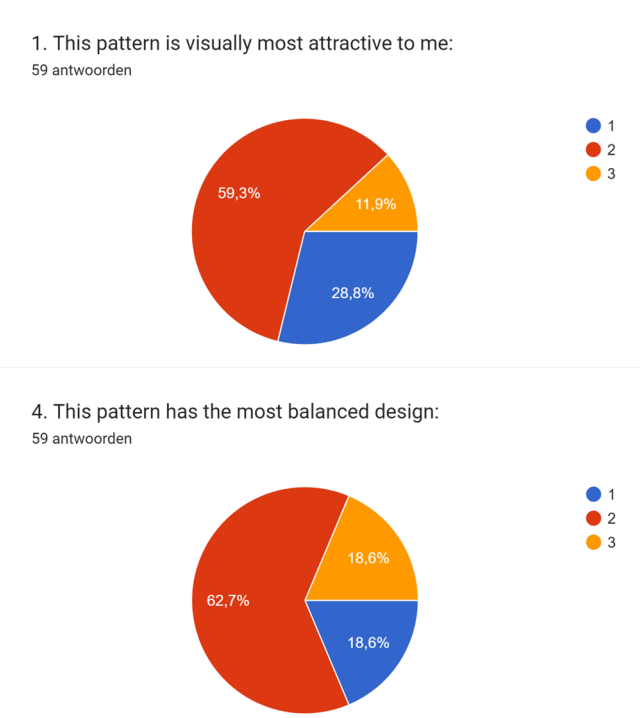


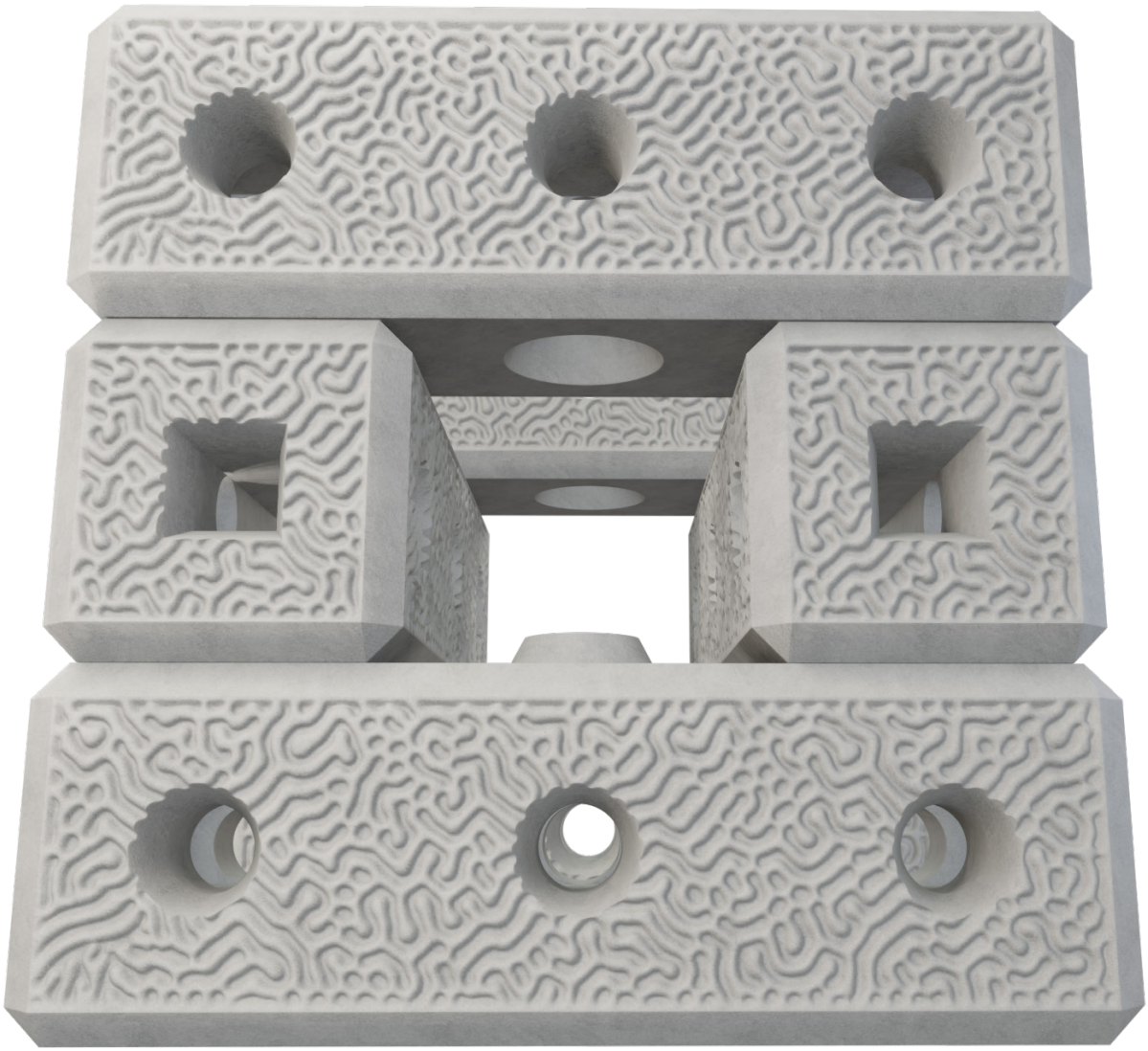
Figure 65: *The two general aesthetic questions, for which both pattern 2 clearly scored best.*

7

Proposed pattern

In this Chapter renders of the final proposed pattern applied to the ReefBlocks are presented and visualisations of potential future marine life in and around the blocks show the intended reef inhabitants, based on the micro and meso marine spatial planning.

With very small sections of the final design, taken from Reefy's logo, were used in a microalgae test to test the effects of the structure and texture designs in a lab setting. Additionally, a larger section of the final design is produced into a form liner for future field tests with the proposed pattern in a real marine context, by Reefy.



7.1 | Design features

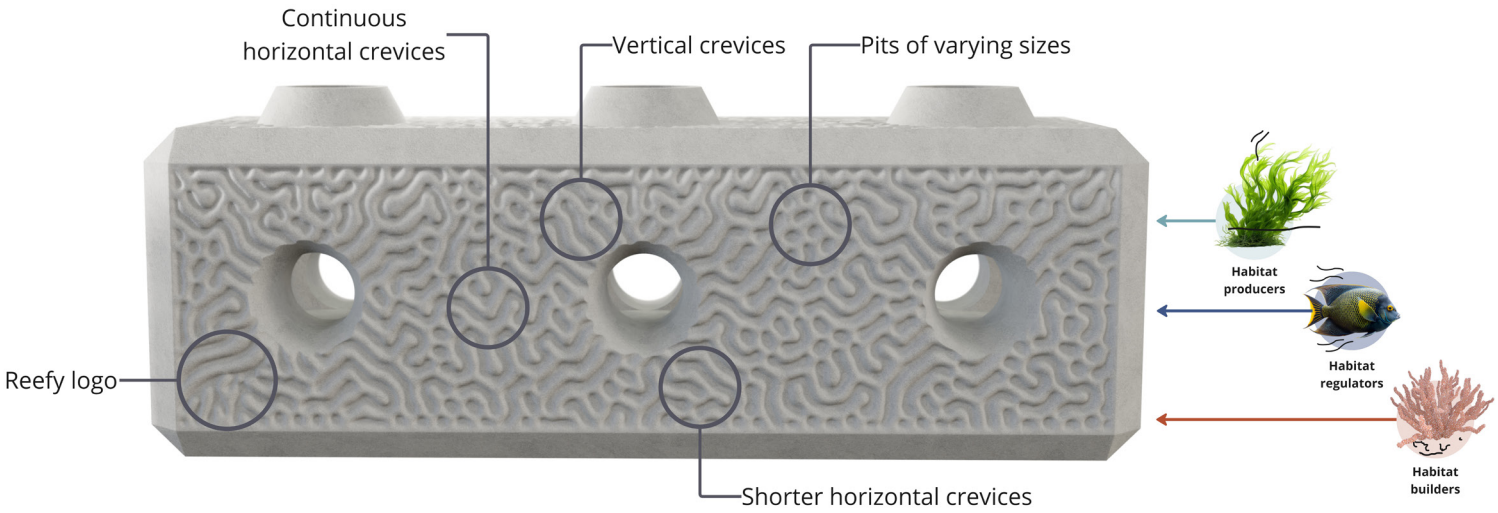


Figure 66: *Final proposed pattern and the meso spatial planning.*

The proposed final design implements the meso marine spatial planning as indicated in Figure 66. Including Reefy's logo and the design features that focus on the different reef inhabitants.

And has a balanced look and feel, reprentative of brain corals, also in configuration with other ReefBlocks as depicted in Figure 67.



Figure 67: *ReefBlocks with the final proposed pattern in configuration.*

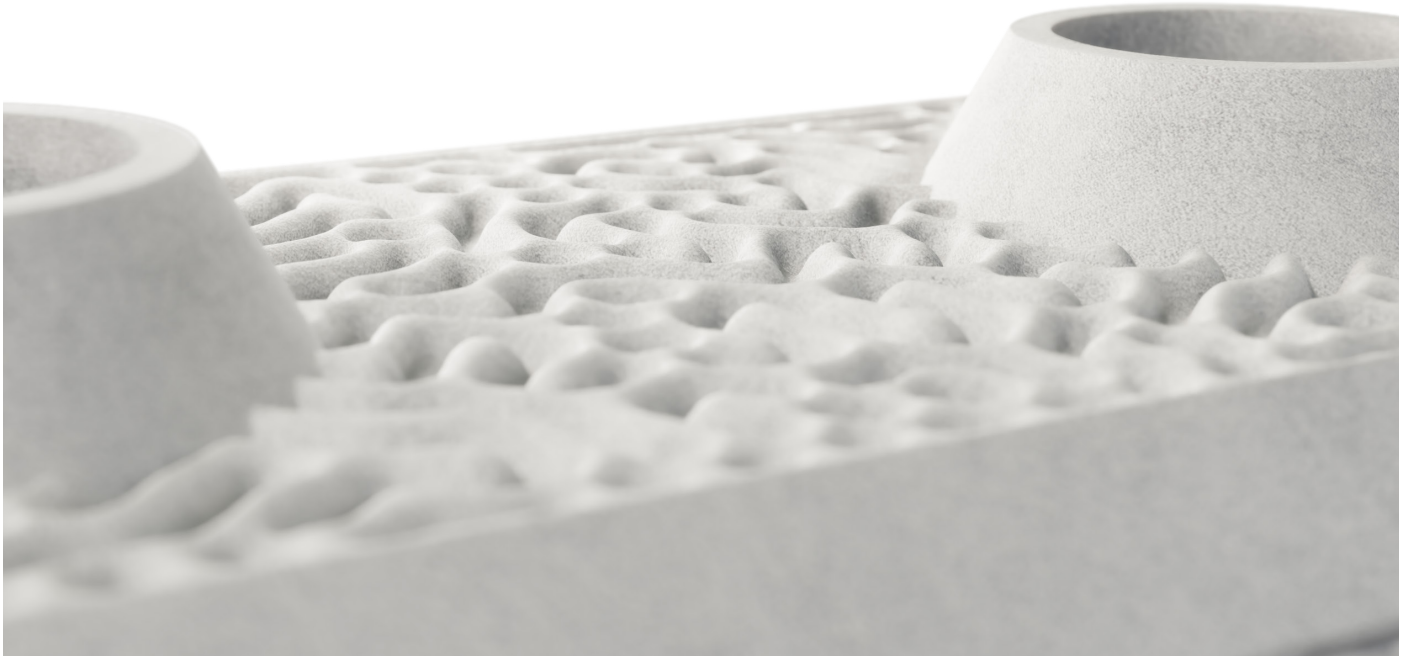


Figure 68: *Close up of the surface structure.*

At centimeter-scale the surface structure has smooth transitions (Figure 68) with a gradient creating wider crevices at the bottom towards more narrow and vertical oriented crevices at the top.

At millimeter-scale the surface texture has translated those smooth transitions to a gradient of more and less present grooves (Figure 69).



Figure 69: *Close up of the surface texture in a render (in this image the surface texture is more faded than in real-life (see Chapter 7.4).*



Figure 71: *Focus for habitat producers on the top half.*

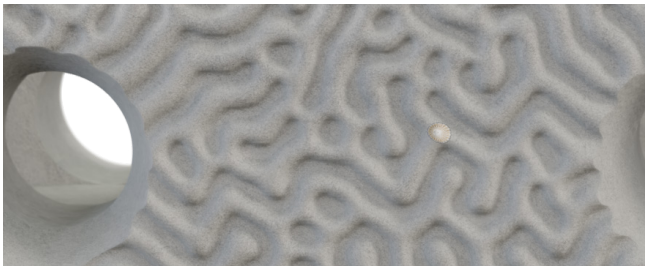


Figure 72: *Focus for habitat regulators in the middle.*

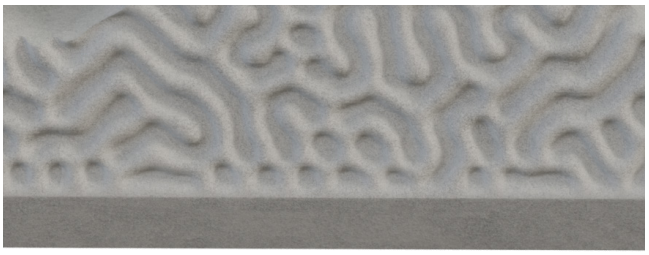


Figure 73: *Focus for habitat builders at the bottom.*

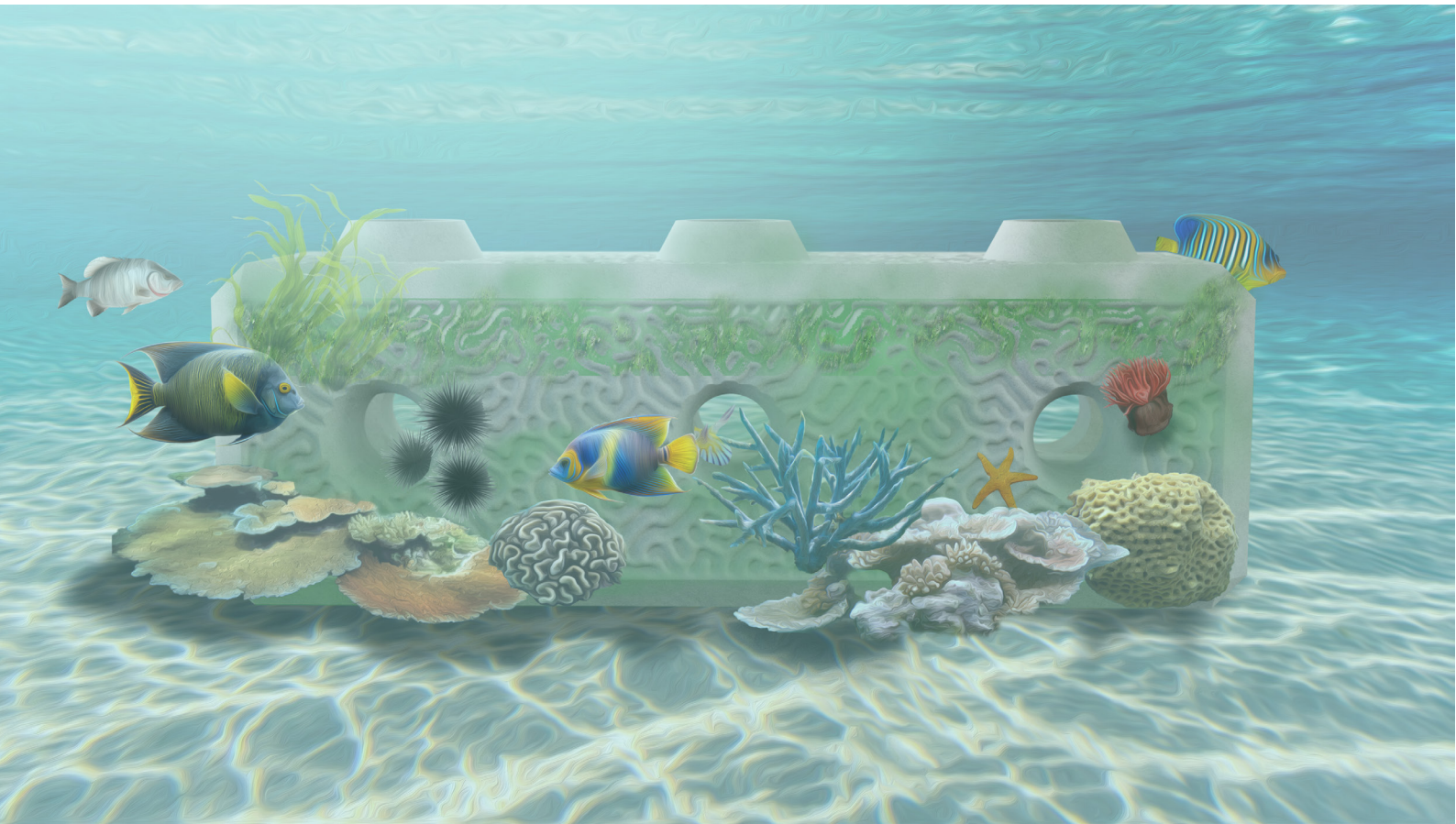
7.2 | Expected reef formation

The visual depicted below, shows the expected reef community distribution in a couple of years, in a potential scenario for warmer climates where the habitat builders are mainly corals (Figure 70). The depictions here are based on what the different design features, orientations and surface texture are designed for:

- **Figure 71**: Moreover vertically oriented crevices on top with the additional pits of varying sizes. With slightly wider 'lanes' for habitat producer focus at the top of the structure to facilitate this.
- **Figure 72**: Moreover continous horizontal crevices, as pathways dividing the top half from the bottom half. Creating a barrier of shadow against algae because the bottom half is more focussed for habitat builders. Longer crevices allow for more room for small habitat builders to refuge in.
- **Figure 73**: Moreover intermittent horizontal crevices and pits that allow a multitude of habitat building species to colonize a microhabitat, wider crevices that create more shadowed areas are created to facilitate this.

But It will be very interesting to see what real nature will make of the structure in a few years time, when Reefy has conducted field tests with the pattern design.

Figure 70: *Render of the ReefBlock configuration including the proposed pattern in a marine context.*



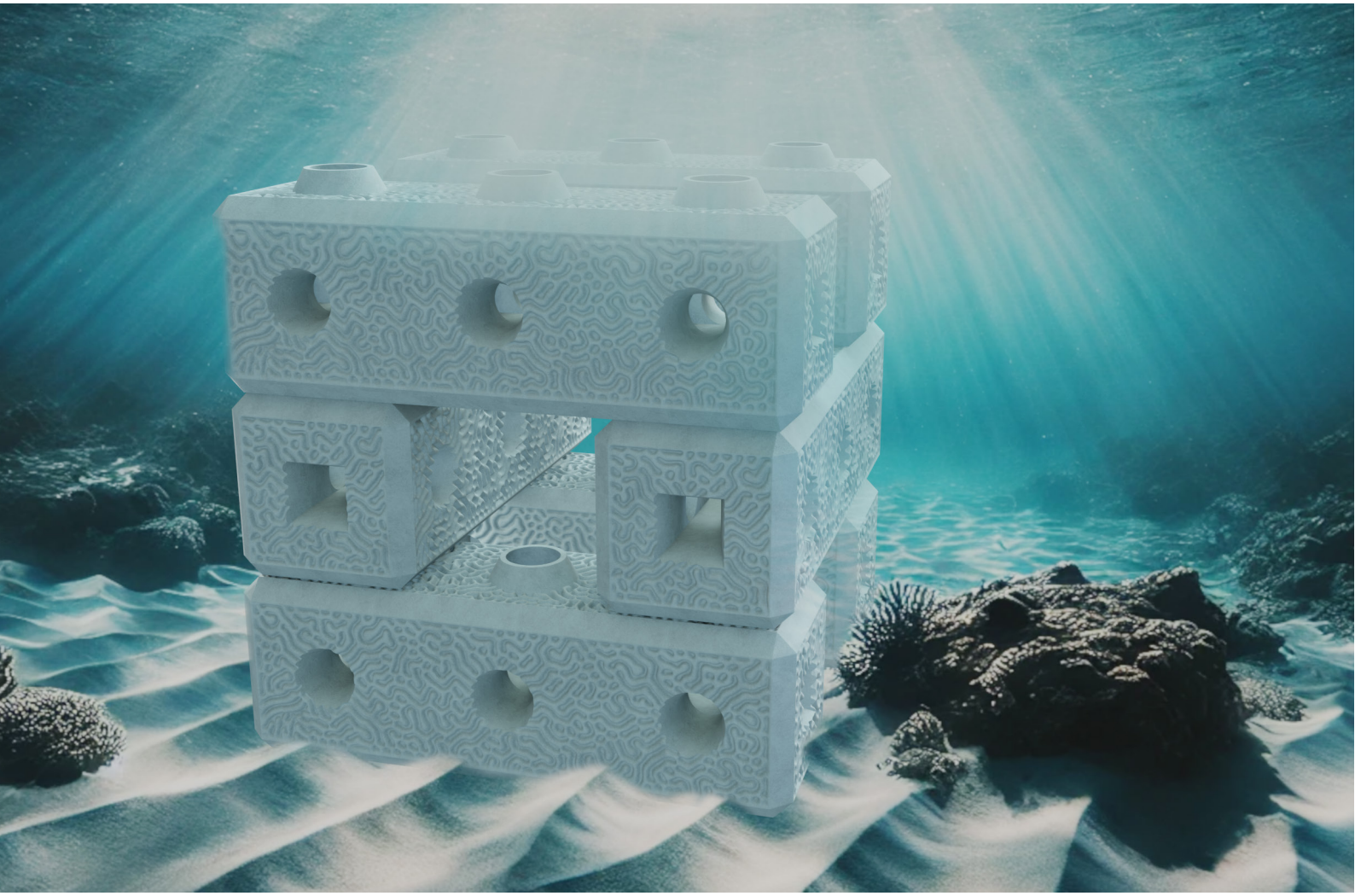


Figure 74: *Render of the ReefBlock configuration including the proposed pattern in a marine context.*

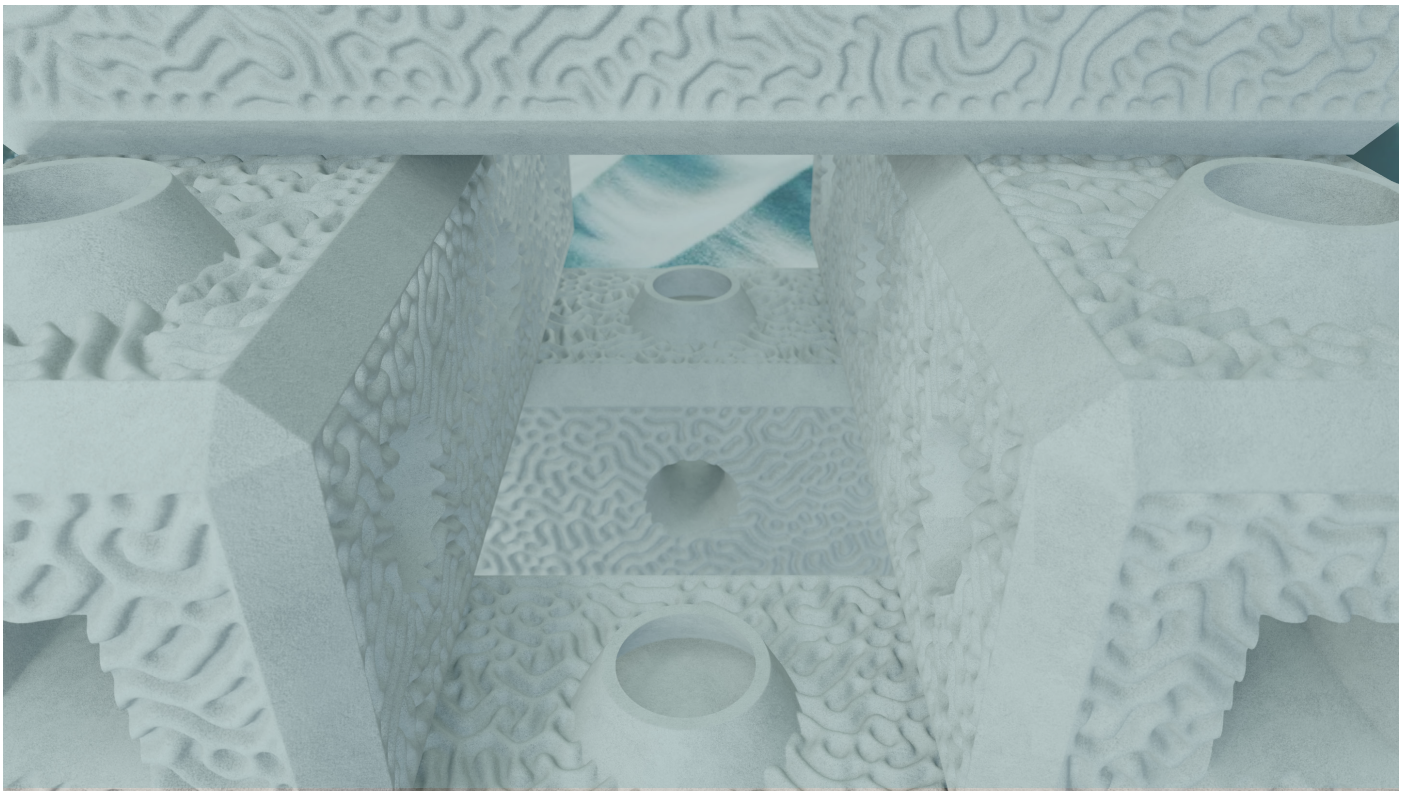


Figure 75: *Underwater scene of the lee area in between the ReefBlock configuration with the proposed pattern.*

7.3 | Microalgae testing

In the marine life overview, microalgae are the micro-habitat producers that are often one of the first pioneering species colonizing the reef surfaces. Their role in the reef community is to provide other marine life with important nutrients. However, in case microalgae growth is not controlled by grazers, they have the tendency to take over entire surface areas. The spores or micro- and macroalgae are the main competitors of habitat building larvae, that seek for a place to settle permanently.

The distribution of fine textured and illuminated areas over the entire surface area of the ReefBlock, allows algae to grow on pathways that are perfect for grazers to use. It is hypothesized that by alternating those pathways with more shadowed and deeper horizontal structures with higher relief texture, the microalgal growth can be obstructed in some areas.

The main purpose of the microalgae testing was to compare the effect of different surface structures and textures, applied to the front of concrete prototypes, on biofilm formation by microalgae, in a controlled lab environment. This study aimed to better understand the influence of surface geometry on microalgae settlement and growth, with regard to variable surface texture and structure. Based on this experiment, we can say where microscopic pioneering species will likely settle. And if the proposed pattern design influences where microalgae grow and to decide if any design changes need to be implemented. Experiments were conducted at IDE Biolab.

For the microalgae test the results were evaluated based on visible development. Conclusions were drawn with regard to the effects of the structural and the textural design features and an evaluation of effective strategies to influence microalgal growth (and assuming the same for macroalgae).

7.3.1 | Experimental setup

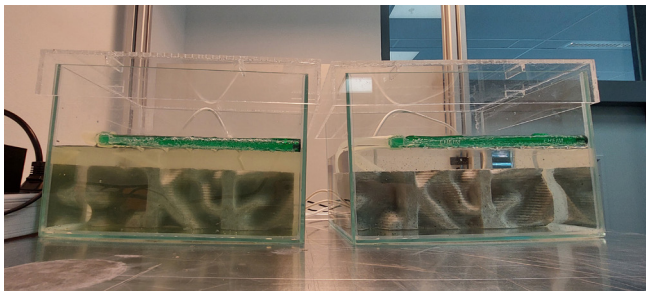


Figure 76: *Microalgae test setup, inside the IDE Biolab.*

Several key decisions were made regarding the experimental setup (Figure 76), the selection of algae strains and the materials used.

Abiotic conditions

In order to test the influence of physical geometry on microalgae growth, it was made sure that all abiotic conditions, accept for the surface structure and texture were kept as constant as possible throughout the experiment. This way, more useful conclusions could be drawn from this experiment.

Salinity level This was determined by the specific culture growth medium for the chosen microalgae strains for the best growing conditions and was maintained constant throughout the experiment. The culture medium used for both was “BG-11”.

Temperature Usually, you keep the microalgae cultures in an incubator with the constant ideal temperature of 22°C. However, due to their size, the tanks had to be placed outside it in the entrance hall of the bio lab, where the temperature has beens relatively stable throughout the experiment, around 20°C.

Light availability Additionally, an incubator keeps the algae on a biological clock of 12 hours light and 12 hours dark each day. In order to recreate this outside the incubator, a controllable light panel with diffused lighting was hung right above the tanks.

Water velocity The water has to be circulated in some way to avoid microalgae sedimentation at the bottom of the tank (Morin et al., 2018) and to “simulate” ocean conditions. The circulation of water simulates water turbulence caused by waves hitting a ReefBlock. Controlled by using pumps connected to a circuit board, allowing adjustments to the water flow via a rotary encoder, if needed.

Tank setup

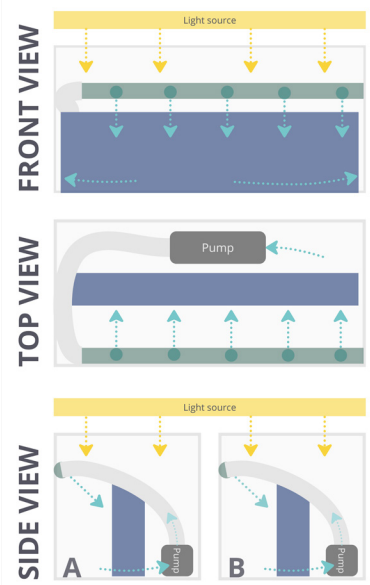


Figure 77: *Schematic of the experimental setup.*

In the experimental setup it was tried to keep the abiotic conditions as constant as possible. A simple setup was constructed, where the prototype forms a wall in the middle of the tank (Figure 77). Behind it, the pump connects to a pipe with holes, on the opposite side of the tank, via silicone tubing. As described, the tanks were placed in the entrance hall. And this location allowed me to much easier check on the algae and take pictures of the progress, without the need to move the tanks each week.

It was decided to build two tank setups, in order to be able to compare two different types of algae strains.

Prototypes

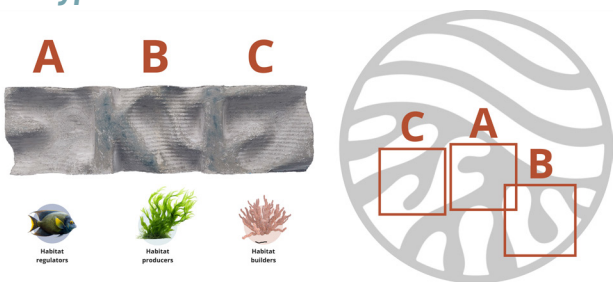


Figure 78: *The three different samples in the concrete prototypes, based on the preferences of the reef inhabitants.*

Sample selection was based on the meso/micro spatial planning with regard to the three identified reef inhabitants:

A. **Habitat regulators**: Large pit with a width of 80mm and depth of 30mm, and millimeter-scale grooves only on the protruding features.

B. **Habitat producers**: Shallow intermittent vertical crevices and pits (widths of 10-20mm), with many ridges (depths of 0mm) in between, as well as the most surface texture on millimeter-scale of the three samples.

C. **Habitat builders**: Deeper horizontal crevices, with a fade of 1-3 millimeter-scale texture.

On the centimeter-scale three samples of the surface structure were selected from Reefy's logo (Figure 78), as it was decided that their logo should be implemented literally in (a part of) the pattern design. In this way, the pattern could still evolve in further iterations, while the microalgae testing was already up and running.

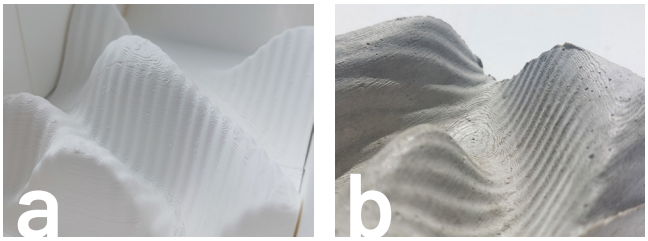


Figure 79: *Close-ups of the surface texture in a) the mold and b) the used prototypes.*

On the millimeter-scale, the halftone effect was applied creating visible grooves. (Figure 79).

Scale and dimensions The pattern samples were produced at a scale of 1:1, in order to understand the influence of the geometry compared to algae growth with 1:1 pattern design dimensions (see Figure 78).

Prototype design One 'morphed prototype' was created that connects the three samples of the pattern design, with two smooth and flat control areas in between (Figure 78). The prototype was made to fit perfectly over the length of the tank, with a little bit of play on the sides (290x80x30mm).

Material choice A material test was conducted to compare different cement mixes and materials (Appendix E). Following these findings, the prototypes were made with a mixture of approximately 60% CEM-III and 40% sand, similar to the real material used for ReefBlocks.

Algae strains

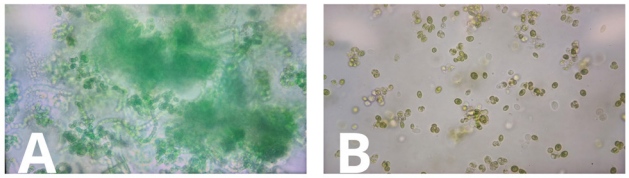


Figure 80: *Microalgae strains under the microscope, with A) Nostoc sp. and B) Scenedesmus sp.*

In order to identify the most suitable microalgae strains for the experimental setup, two initial microalgae tests were performed (Appendix E). The selection and suitability for the microalgae test were based on:

- **Visibility**: their color on top of the prototype.
- **Adhesion behavior**: their interaction with the cementitious material.
- **Survival**: they need to be able to survive being submerged with a concrete prototype.

From these tests, the following algae strains were selected (Figure 80):

A. ***Nostoc* sp.**: a filamentous multicellular organism, belonging to the Cyanobacteria phylum. As they grow, they tend to form one large connected film over the surface.

B. ***Scenedesmus* sp.**: a unicellular but colonial organism from the Green Algae group, known for its adaptability for survival.

Procedure

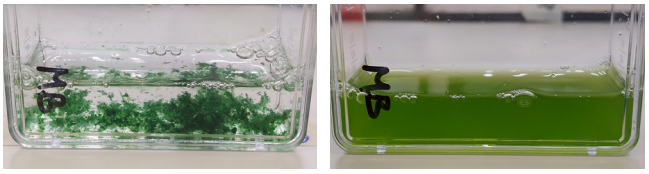


Figure 81: *Growing microalgae culture batches.*

Five weeks prior to starting the microalgae test the two selected microalgae strains were grown, starting from small batches of about 10mL microalgae to 10mL BG-11 medium (Figure 81). Each week this volume was doubled, which means that after five weeks a volume of about 320mL was achieved. Weekly the algae were checked if they were in semi-continuous growth under the microscope. It was decided to use a 1:50 ratio of algae to medium for the microalgae test. And the BG-11 medium was diluted to a ratio of 50:50 with sterilized demi-water.

Two weeks prior the concrete prototypes were submerged in demi-water that was refreshed each week. At least 1 week (or more) of submerging the prototypes is necessary before introducing concrete to the medium and microalgae.

The necessity for this was discovered during an earlier test for microalgae strain selection and is because concrete needs time to leach out, otherwise it will react with the medium and form clouds which kill the microalgae (Appendix E).

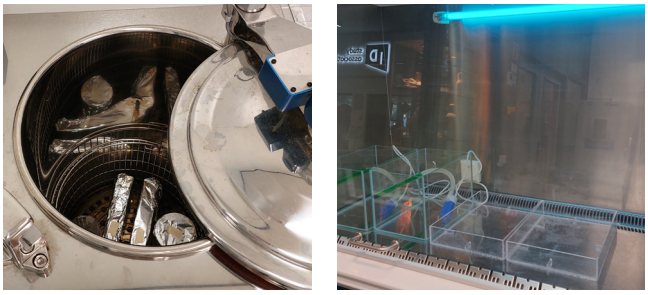


Figure 82: *a) Prototypes and tools inside the autoclave; b) Tank setups sterilized by UV light in the flow cabinet.*

The day before the entire test setup and tools used for setting up the test were sterilized. The prototypes and tools to adjust the prototype's position inside the tank were autoclaved (heated up to about 130°C) (Figure 82).

However, the tank setup was too large and included plastics, so these could not be autoclaved and were sterilized by drenching them in ethanol and letting that air dry. The pump was sterilized by running the ethanol through it for at least 30 minutes. The entire tank setup was then sterilized using UV under the flow cabinet and left over night (Figure 82).

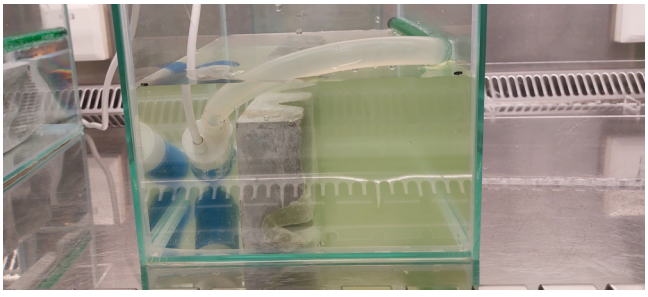


Figure 83: *Submerged prototype in tank during setting up the test.*

The day of starting the microalgae test for each tank of the microalgae test a total of 6 liters of medium and demi-water mixture was used to fill the tanks just enough to submerge the prototypes entirely (Figure 83).

7.3.2 | Results

The growth behavior of the microalgae in the test setup was evaluated for a total of four weeks, after that, the visibility inside the tanks got so poor that the prototypes were taken out of the tanks to take pictures. See Appendix F for all evaluation notes per week.

The algae needed some time to settle with their new and dynamic environment. On Day 14 (Figure 87) the results were best visible in the test setup itself. Already it showed a very clear development of both algae types on the surfaces.

Day 0

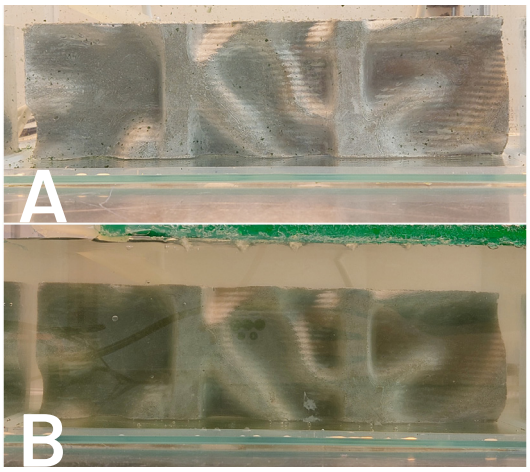


Figure 84: *Day 0 of the microalgae test.*

Day 1

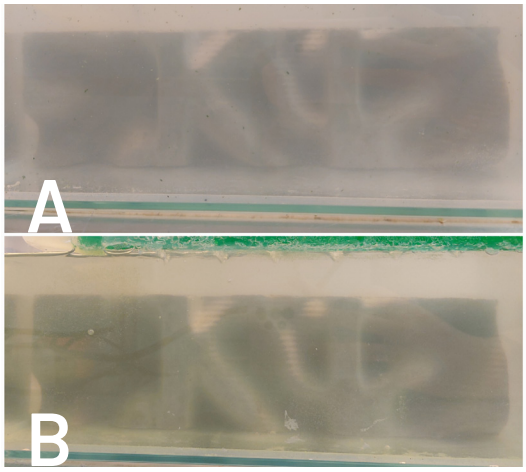


Figure 85: *Day 1 of the microalgae test.*

Day 7

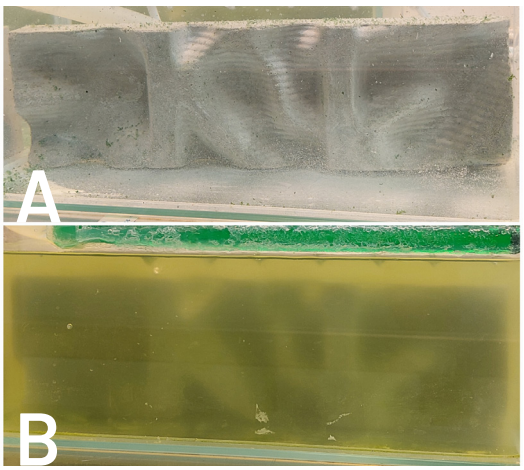


Figure 86: *Day 7 of the microalgae test.*

Day 14

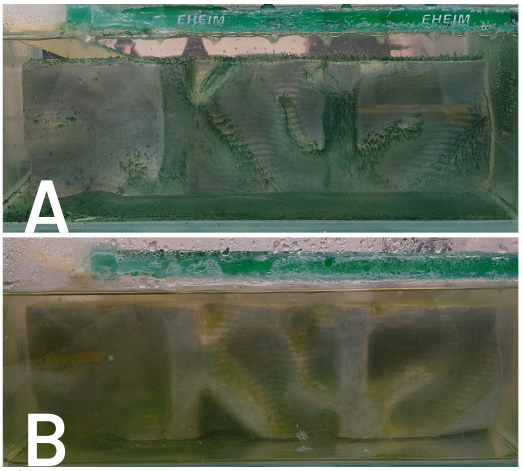


Figure 87: *Day 14 of the microalgae test.*

Day 21

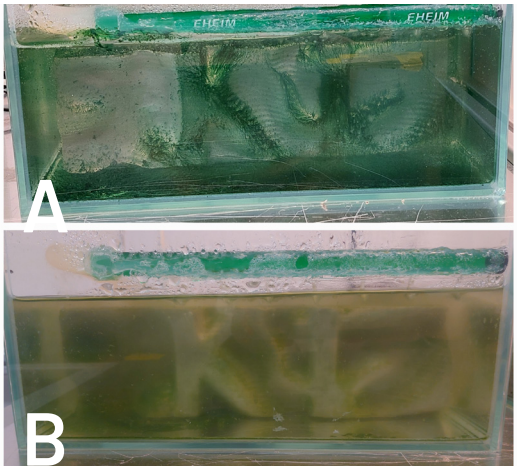


Figure 88: *Day 21 of the microalgae test.*

Day 28

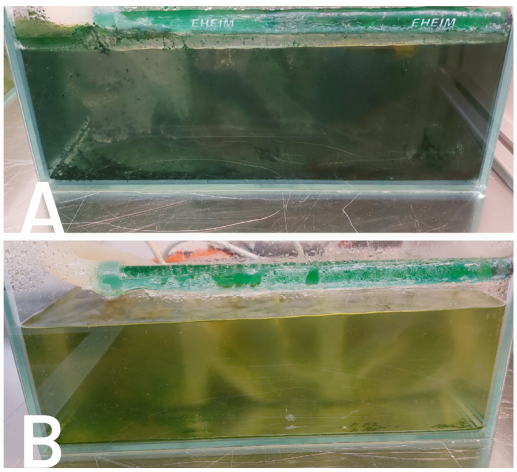


Figure 89: *Day 28 of the microalgae test.*



Figure 90: *Final resulted algal growth of Nostoc sp. on the concrete prototype after 42 days of being in the microalgae test.*

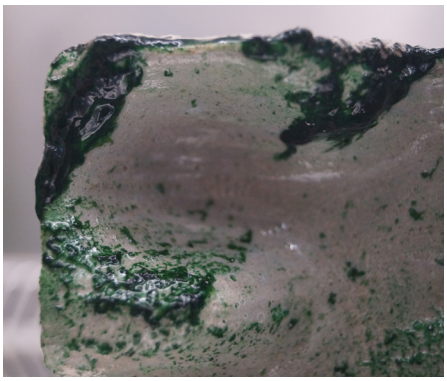


Figure 91: *Nostoc sp. close-up sample A.*

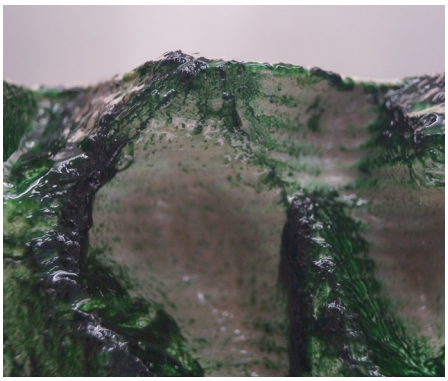


Figure 92: *Nostoc sp. close-up sample B.*

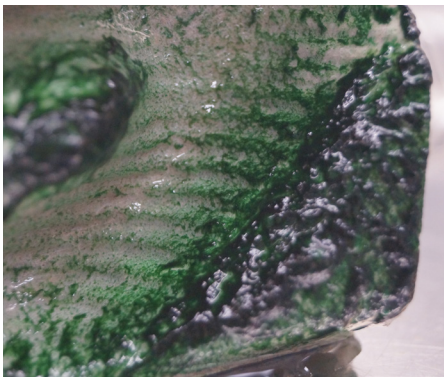


Figure 93: *Nostoc sp. close-up sample C.*

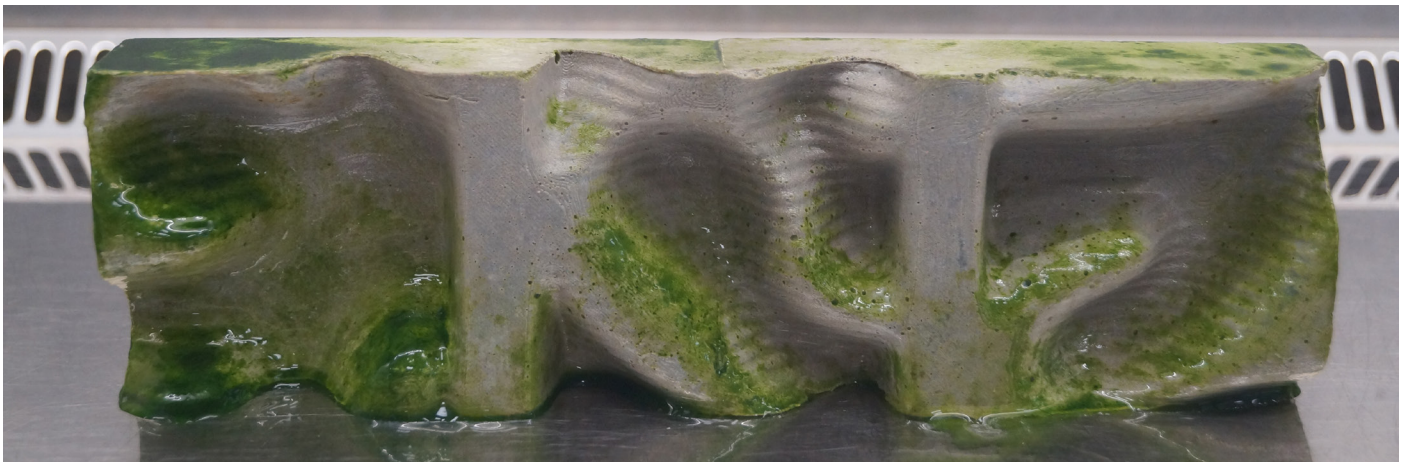


Figure 94: *Final resulted algal growth of Scendesmus sp. on the concrete prototype after 42 days of being in the microalgae test.*



Figure 95: *Scenedesmus close-up sample A.*



Figure 96: *Scenedesmus close-up sample B.*

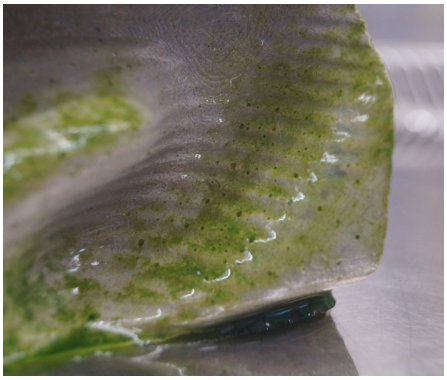


Figure 97: *Scenedesmus close-up sample C.*

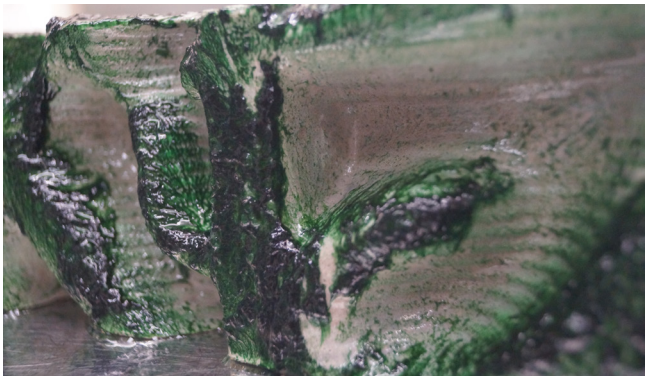


Figure 98: *Clear division line with the sidewalls by Nostoc sp.*

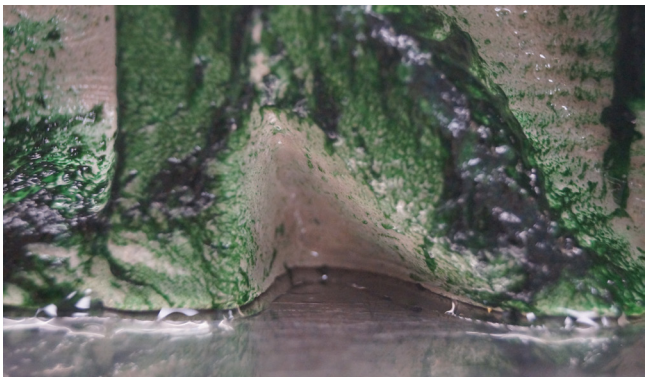


Figure 99: *Clear avoidance of overhangs by Nostoc sp.*

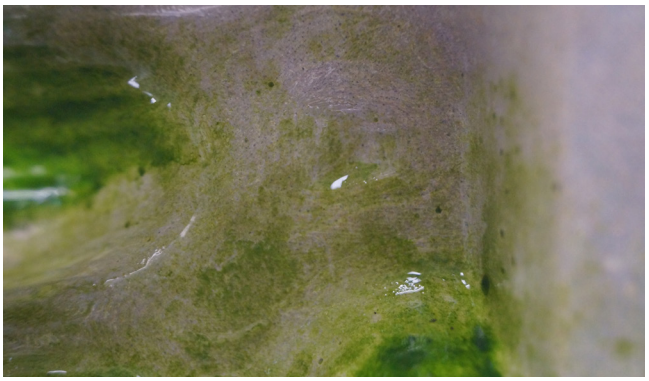


Figure 100: *Scenedesmus sp. is found in medium density in the deep structure of sample A where light is more avaliable than in the more narrow crevices and a presence on the sidewalls.*

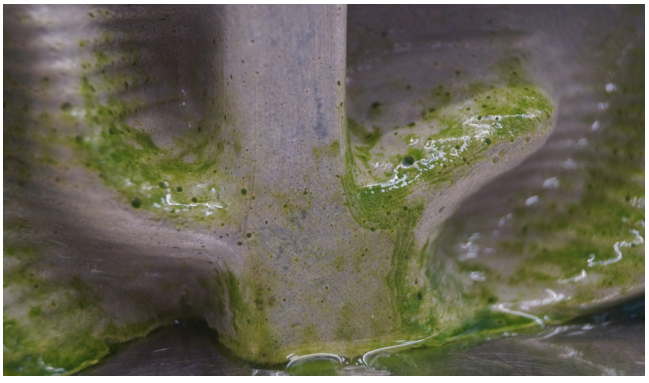


Figure 101: *Clear avoidance of exposed smooth surfaces and preference for slightly sheltered depressions by Scenedesmus sp.*

7.3.3 | Conclusions

Figure 90-93 show the development of the Nostoc and they very clearly prefer illuminated areas, as expected with microalgae. Figure 93 shows how the high density fades out towards the deeper structure, on top of the millimeter grooves. And the Nostoc is not found at depths deeper than 10mm.

Figure 94-97 show the development of the Scenedesmus and they clearly avoided the smooth (control) surfaces (Figure 101), except for those in a deeper structure (Figure 100). Scenedesmus also has higher densities in more illuminated areas (Figure 95), but seem to settle in the depressions of the grooves (Figure 96 & 97).

This is interesting as they show opposite behavior in these dynamic water conditions with regard to where they attach. Nostoc clearly only prefers the lightest, most exposed areas, and Scenedesmus clearly prefers the slightly more sheltered areas, avoiding being exposed to the water currents.

This means that Scenedesmus actually shows behavior closer to what is expected from habitat builder larvae; meaning that such an algae type may be a larger competitor for space than the Nostoc in the reef community. However, at depths below 20mm, Scenedesmus was found much less (Figure 100). So, to provide space for habitat building larvae, deeper structures or harsher transitions may be advised.

The microalgae test was a validation for the use of grooves on millimeter-scale and the orientation of crevices on centimeter-scale, which both clearly influenced the algal settlement behaviors. For the Scenedesmus, the grooves at depths between 0-20mm proved crucial for their settlement behavior

Harsher transitions create harsh shadows and that can prevent algae from growing at specific areas (Figure 98 & 101). When the transitions are softer, the algae tend to grow on the horizontal top half of the overhangs (Figure 93, 95 & 97).

Both algae avoid horizontal overhangs (Figure 91, 96 & 99) and so the equal distribution of horizontal oriented crevices can prevent microalgae from taking over all surfaces.

From the test, it can be concluded that an average depth of 20-30mm can prevent (micro)algal colonization. This is a good argument for deeper crevices. The use of grooves, even at such a small scale, clearly influence algal settlement, creating more potential for habitat building larvae.

7.4 | Form liner for future testing

In order to help Reefy along with actual field tests using the proposed pattern design from this project, I produced (in-house) a 400x400mm PU form liner (Figure 106). This form liner is a small part of the full-size pattern design for the ReefBlock (Figure 102). The selected sample was taken from the middle of the ReefBlock, in order to represent as much of the meso spatial planning as possible (Figure 103).

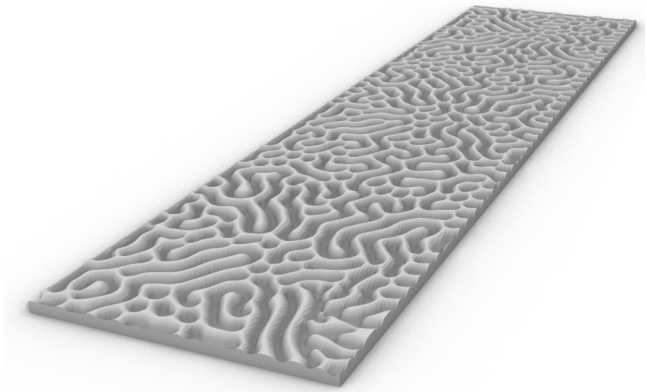


Figure 102: *Depiction of what the full sized form liner will look like.*

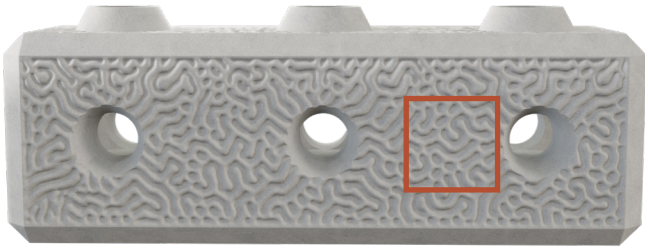


Figure 103: *Sample taken from the proposed pattern design.*

Given that the design is closely related to the current form liner produced by Reckli, the costs of making this pattern remain similar to existing solutions. Furthermore, the method used to create the three-dimensional surface guarantees that the form liner will always be releasable from the concrete. The way the image is projected onto a grid of adjacent points ensures that these points can only move downward, preventing the creation of undercuts or overhangs in perpendicular planes.

After conducting a risk assessment of the substances in the liquid polyurethane (PU) rubber, it was determined that it was safe to use, provided I worked inside a fume hood and wore the appropriate personal protective equipment (Figure 104). One of the substances in component A contains a carcinogenic agent when inhaled, but working within the fume hood provided a safe environment for in-house production of the form liner. I want to thank Mascha Slingerland for helping me realize the importance of safety when working with such chemicals.

One of the advantages of the parametric model is that it can seemlessly change the outcome from a large and complete ReefBlock to a flat tile to a mold around that flat tile that is either the positive or negative of that same pattern, simply by toggling some functional blocks on and off.



Figure 104: *Production using the appropriate and safe work environment when working with liquid PU rubber.*

The mold for the form liner was produced with 3D printed parts, similar to how the concrete prototypes for the microalgae testing were made. Because the mold for the form liner was created using the same parametric model, I was able to use the exact model from the concrete prototypes and simply adjust the dimensions of the mold. I didn't need to change much about the model, except for ensuring that I didn't invert the final pattern, as the form liner needs to be a negative of the proposed final design.

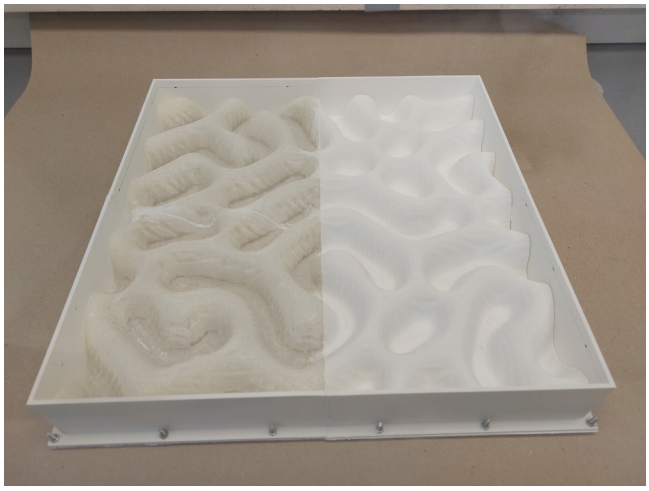


Figure 105: *The mold for producing the rubber form liner.*

During the production process, I added blue chalk powder to the two components of the material being mixed. This allowed me to verify if the components were blended well and also gave the form liner a more visually appealing color. Using acrylic sealant worked effectively to assemble the mold, ensuring that no gaps were left and the mold was completely leak-proof. When it came time for demolding, the acrylic sealant was easily removed with a Stanley knife, making the process smooth.



Figure 106: *Pouring of the form liner.*

Pouring the form liner in increments proved to be a learning experience. The PU rubber dried quickly, and as I poured subsequent layers, the earlier portions were already beginning to harden. Deep crevices formed pools of rubber, but because I poured in smaller increments, the rubber didn't fully distribute across the mold surface at once. It took over ten increments for the material to cover the entire surface evenly.

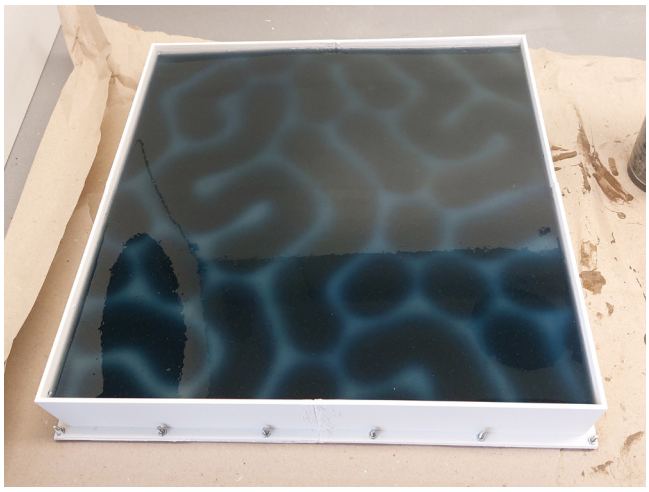


Figure 107: *Rubber form liner curing in the mold.*

With the production of the form liner it was confirmed that the design perfectly meets the production requirements. Additionally, the wide and deep crevices create very stirdy mold protrusions. Only, the protrusions that were cut-off due to the fact that this form liner is a section of the full-size ReefBlock form liner, are thinner and therefore more frail. But this will not be an issue on the full-size form liner.

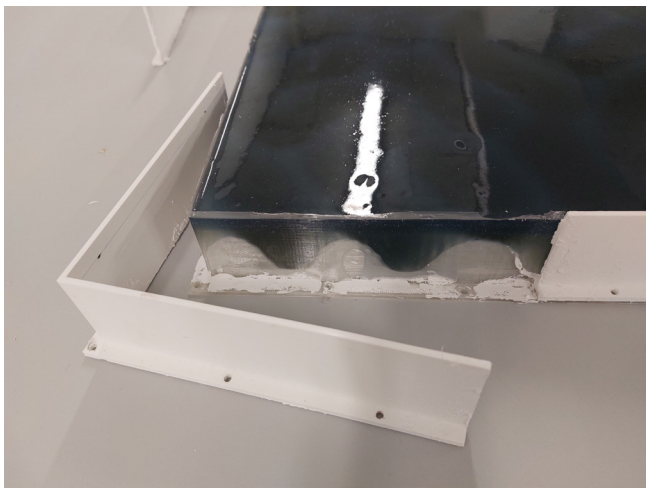


Figure 108: *Demoulding of the rubber form liner went relatively easy.*

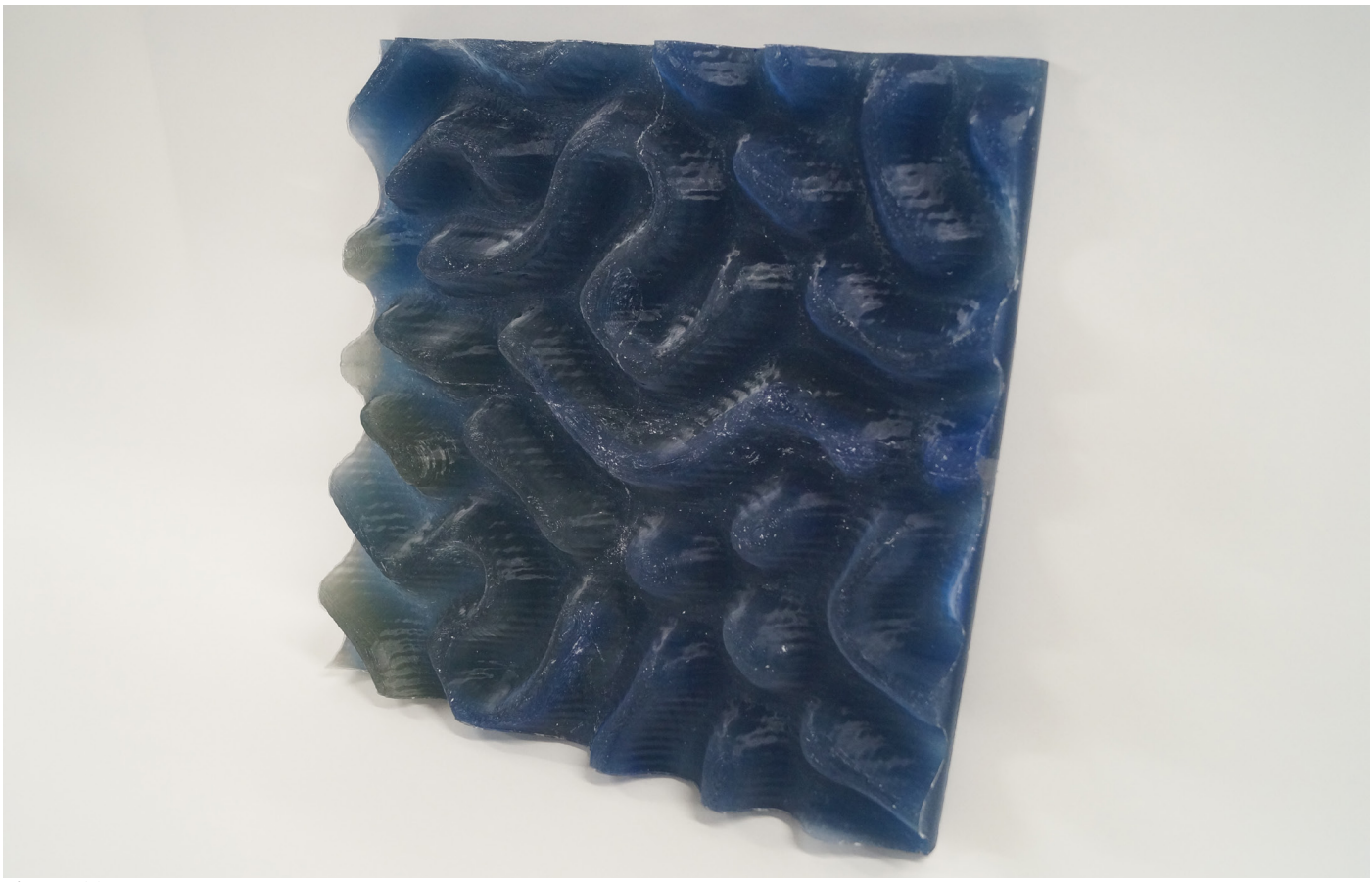


Figure 109: *Produced 400x400mm form liner with PU rubber.*

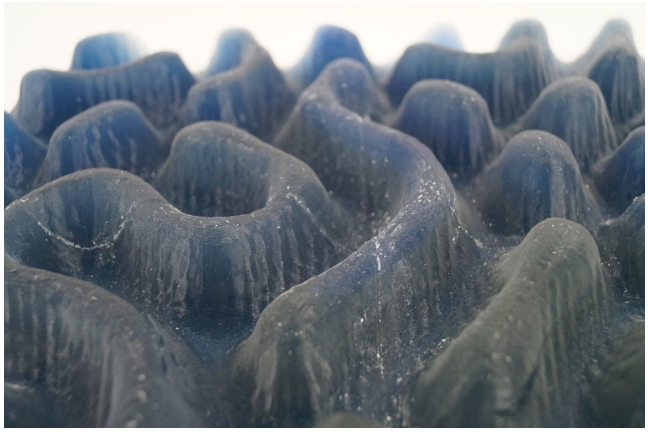


Figure 110: *Close-up on the reversed crevices and pits from the surface structure.*



Figure 111: *Close-up on the imprinted surface texture created with the halftone effect and by the 3D printed layers of the production mold.*

Despite that this form liner is only a small section of the complete proposed pattern design for the ReefBlock, the concrete tile includes all ecological requirements:

- Pits in varying sizes;
- Vertical and horizontal shorter crevices;
- Horizontal continuous crevices
- Surface texture on millimeter-scale

It is expected that at least 100 concrete tiles can be produced for future field tests with the durable PU form liner. Figure X below shows what the concrete tiles will look like. Enabling the concrete to enhance biodiversity on artificial reefs or quay walls.

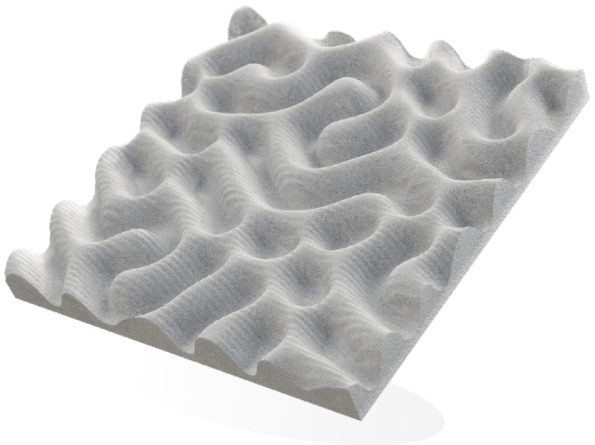


Figure 112: *Render of a concrete tile that will be made with the produced form liner.*

7.5 | Conclusions

7.5.1 | Desirability and the ecological requirements

The generative art method allowed me to guide the outcome using the initial image, which gave me the ability as a designer to maintain control over the design while meeting the spatial planning requirements for the reef inhabitants. At the same time, it provided an opportunity to experiment with different visual aesthetics at a rapid pace by utilizing available technology. This method inherently created the two most crucial design features: crevices and pits in varying directions and sizes. Discovering this method after defining the meso and micro spatial planning marked a major breakthrough in my project.

The deeper crevices play a significant role in the overall design. They create larger sidewall surface areas that have been proven to be preferred by habitat-building larvae and habitat regulators. However, there is a limitation with the depth of the crevices, as the habitat regulators can only use crevices up to 30mm for refuge. The deep crevices not only provide additional shadowed spaces, which reduce surface temperatures—a benefit considering climate change—but they also allow clusters of marine life to form within their own microhabitats due to the varying lengths.

The effectiveness of the pattern design largely depends on the light and shelter it offers to marine life at different scales. I concluded that spatial planning was necessary to support the three types of reef inhabitants, which led to a final design incorporating both meso crevices and pits, as well as micro grooves.

I conducted an experiment using microalgae, which act as micro primary producers, functioning as ecosystem engineers. Since microalgae can colonize surfaces quickly, they provided results within the limited timeframe of my graduation project. The microalgae test revealed a distinct division between the sidewalls and exposed front, particularly with Nostoc sp., which left space available for habitat-building larvae. The test also showed that the depth of the crevices had a significant effect on microalgal presence and growth behavior.

The 3D grooves, designed with a texture at the 3-5mm scale—slightly larger than initially desired for habitat-building larvae—proved highly effective during the microalgae test. The different algae strains showed contrasting settlement behaviors, with Scenedesmus sp. preferring the depressions in the grooves, a behavior similar to that expected of habitat-building larvae. This indicated that the grooves have strong potential to provide millimeter-scale shelter.

Additionally, in the post-processing steps for the 2D image generation, less surface texture was applied to the deeper or shallower areas using the halftone effect. This matched perfectly with the findings that at depths close to 0mm, the smoother surfaces support only algae, making them ideal for habitat producers, while at depths of around 30mm, no additional texture was needed for habitat regulators.

Overall, designing for the climax community required understanding how marine life develops through ecological succession and how their roles in the ecosystem are interconnected through trophic levels. The project's findings suggest that the pattern design effectively supports these interactions at multiple scales.

7.5.2 | Viability and the stakeholder requirements

The fact that the pattern is generated through a simulation of the natural process observed in brain corals, as well as other life forms, makes the design closely resemble the envisioned lobed brain coral. This approach not only ensures a literal representation of natural patterns but also lends the design credibility, as it is grounded in biological processes.

The use of the generative art method offers a strong business unique selling point by differentiating the design through its connection to natural processes. Furthermore, the stakeholder survey indicated that pattern 2 best met their aesthetic requirements out of the three proposed options. This pattern also provided the most literal resemblance to brain coral, which contributed to its approval.

The deeper crevices in the proposed design allow the pattern design to "last longer" as the reef evolves over time. A more shallow structure will "fade" faster, as it is filled and covered by marine life more quickly. It may be helpful that the pattern remains better visible for longer in the underwater context, for taking pictures about the development of the reef for future presentations showing the great potential of the used pattern design.

7.5.3 | Feasibility and the production requirements

The use of surface texture (millimeter) grooves in the design raises the possibility of increased surface friction during the unmolding process, when the concrete is separated from the form liner. To mitigate this, it is crucial that the grooves are not too defined or deep. The proposed depth has proven to work well, although the groove width turned out larger than expected. As a result, I recommend adjusting the pixel art board size to ensure better control over this aspect.

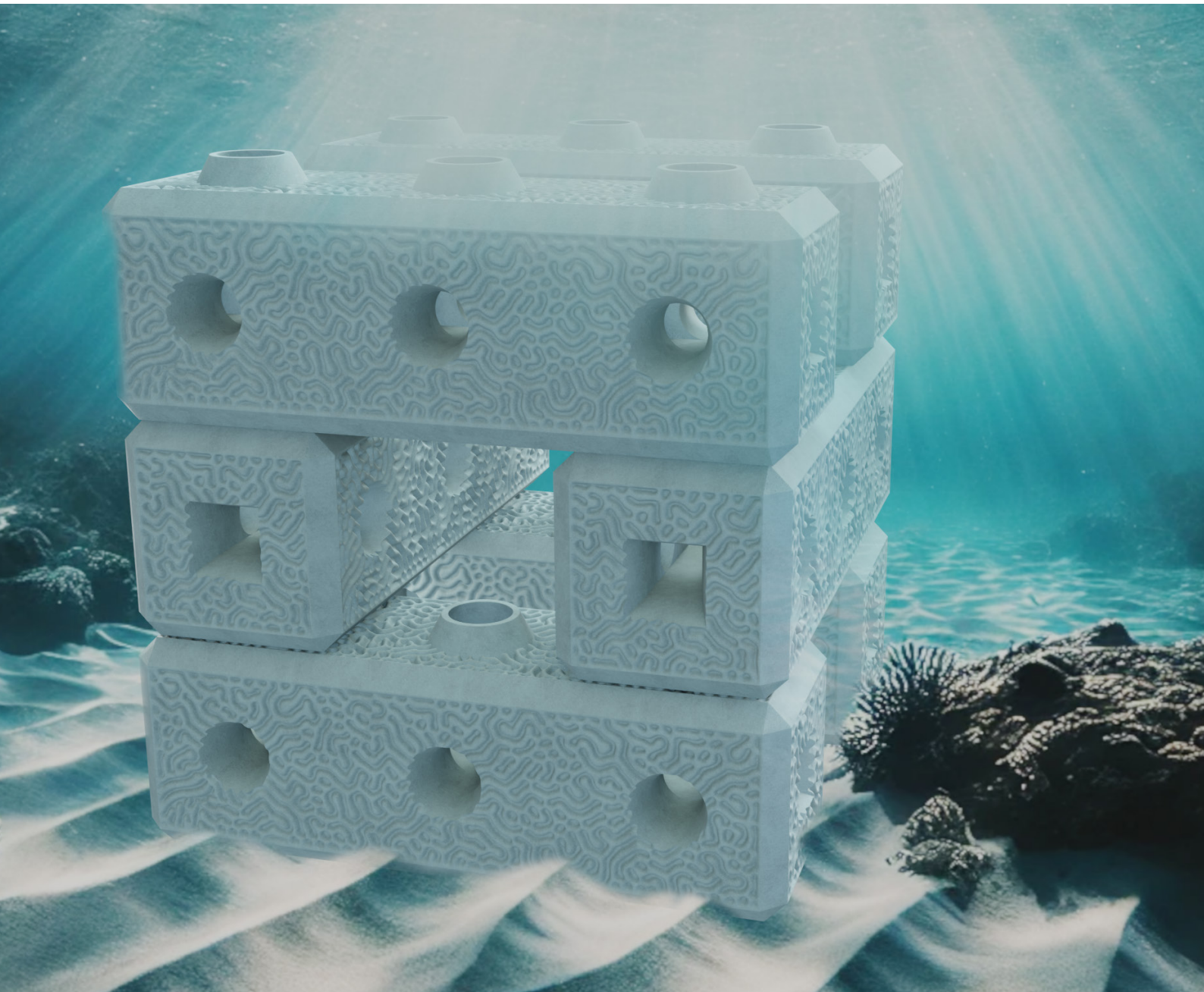
The parametric model, combined with the image sampler tool, plays an essential role in ensuring that the pattern design meets most production requirements. By utilizing gray values and limiting dimensions, the design remains feasible throughout the process. Another advantage of the parametric model is that it inherently creates smoother transitions on the surface. This is achieved by connecting adjacent points on the grid, which is driven by the image input.

Another helpful aspect is the post-processing blur applied to the 2D image. This blur controls how smooth the transitions are and ensures that the width-to-depth ratio of the design features remains around 1:1. By applying the correct amount of blur, the depth is linked to both the distance between lines and the thickness of the lines, enhancing the overall manufacturability of the design.

Moreover, the model accounts for the production constraints of the form liner. Since the image manipulates the grid of points only in the release direction of the form liner relative to the concrete, the design automatically incorporates a draft angle, preventing the occurrence of overhangs or undercuts. This feature guarantees that the design is ready for production. The parametric model also prevents the pattern from exceeding the maximum dimensions, ensuring that all production requirements are met with almost any design.

To validate that the design meets all production requirements, I produced a form liner based on a section of the final proposed design. This step confirmed that the design solves all necessary production constraints and it assists Reefy in moving toward field tests. Importantly, by using similar dimensions to those Reefy currently uses for their ReefBlocks, the production costs remain relatively similar.

8 Discussion



8.1 | Future implementation

8.1.1 | Pattern design

The proposed pattern design as presented in this report, will be produced by Reefy's form liner company Reckli in the near future. This form liner will be used for future pilot field tests of ReefBlocks with the proposed pattern design. In case the proposed design effectively enhances biodiversity in and around the ReefBlocks, my design will likely be implemented all around the world in the future, which is a very exciting prospect.

The possibilities for the future implementation of the pattern design extend beyond its initial use on the ReefBlock. Reefy is interested in expanding their product line by offering a pattern design in smaller, modular tiles that can be applied to quay walls or other types of marine infrastructure that are not their ReefBlocks. Offering a retrofitting solution that can enhance the surface complexity, and with that promote biodiversity. The idea of a "tileable" pattern design introduces the possibility to cover an entire wall with the pattern, without making it look like a repeating pattern. A smaller wall panel would allow the pattern design to be produced as smaller, more manageable tiles, making it easier to scale for different applications.

The use of generative art by means of reaction-diffusion actually enhances the story around the design.

8.1.2 | Future field tests

For the duration of this project, the decision was made to limit the scope and focus primarily on the application of the pattern design to the ReefBlock. The in-house produced form liner represents a small section of the larger proposed pattern design. Conducting field tests with the design is a practical way to gather data and make refinements before scaling up to full ReefBlock implementations. This approach allows for controlled testing and validation before committing to larger-scale production.

8.1.3 | Pattern toolset

The digital tool used to create the surface pattern is applicable to various manufacturing techniques. For example, 3D printing the pattern using different types of materials is growing to become a viable production method for infrastructure. The use of such a production technique that creates distinctive layers, can create the desired surface texture without the need to implement that into the 2D proposed image. Several initiatives are already exploring the use of eco-friendly materials in 3D printing, and this could align well with Reefy's mission.

Additionally, the 2D digital version of the pattern presents branding and marketing opportunities. It could be incorporated into visual designs for reports, promotional material, and even as part of the company's identity. In fact, I used variations of the generated pattern design in this report to improve its layout, illustrating the versatile applications of the design tool.

The pattern toolset is provided to Reefy, in order for them to be able to change the design in a later stage, if desired or deemed necessary if the field tests point out that the pattern design is not as effective for enhancing biodiversity as expected. Or if it turns out that each unique context needs a unique design.

Much of this potential remains to be fully realized, as the primary focus has been the ReefBlock and no tileable pattern design is proposed in the end. However, exploring these other implementations and production methods could help Reefy diversify its product offerings, enhancing its impact on marine environments worldwide.

8.2 | Recommendations

8.2.1 | Pattern design

Currently, the use of the reaction-diffusion tool results in roughly the same line width, and can be varied slightly without creating clear harsh transitions in post-processing steps. With regard to the ecological requirements it may be interesting to create much more varying line thickness, using the reaction-diffusion design tool or an additional generative tool.

Additionally, I would recommend iterating further with design patterns that also have smaller pits implemented, without losing the clear visual lobed brain coral reference. Already, the proposed pattern design looks less like a lobed brain coral with the addition of pits in the design, than without the pits. However, the addition of such 'smaller' pits next to the crevices is crucial for many grazers and smaller habitat builders.

Specific recommendations with regards to the technicalities of the settings and initial images used in the pattern toolset in order to achieve this exact proposed pattern design, are shared with Reefy in a separate document.

8.2.2 | Future field tests

To fully verify whether the proposed pattern design enhances biodiversity in marine ecosystems, it must be tested in natural marine environments. I recommend that these tests be conducted both in intertidal and subtidal zones, as these offer very different conditions and can provide insights into the versatility of the design. And most importantly, to understand whether one pattern design indeed suits all inhabitant types. Testing the pattern design across various marine locations would allow for comparisons between different abiotic conditions and reef communities. Which will also provide important insights for the scientific field of artificial reefs, as there is very little research out there (as far as I was able to find) that has tested the same pattern design with 3D surface topography in such very distinctive environments across the world.

Reefy's operations in Mexico present the ideal opportunity for testing the design in at least two opposite biomes. Mexico's marine biodiversity and abiotic conditions would offer a great contrast to Reefy's current testing site in the Netherlands. Providing important data on how the proposed pattern design performs in varying environments and whether the marine life generalizations that I made for my project are correct or that it is necessary to offer a custom design, tailored to the specific context of the location that the ReefBlocks are placed. These field tests would also help refine the design, ensuring it is adaptable to different ecosystems and enhancing its global applicability.

8.2.3 | Pattern toolset

In terms of the design process, the pattern toolset as I composed and used it during my graduation project, though functional, is not without its challenges. Applying ecological functionalities to the pattern design is a complex, multi-step process that quickly becomes overwhelming due to the number of layers involved in image editing tools like Photoshop.

A parametric tool for generating the 2D image would be a much more efficient solution, allowing for dynamic adjustments to the design without having to manually redo each step. Fortunately, Photoshop's "action groups" allow for some automation by recording the steps required to edit the image, though this is still not as flexible as a parametric tool would be. Moving forward, developing or adopting a more advanced parametric design tool could streamline the process significantly and allow for more complex, ecologically functional designs to be generated more easily. Even greater would be

8.3 | Limitations

8.3.1 | Final proposed pattern design

This research faces several limitations, primarily concerning the validation of the final pattern design in real-world marine environments. One of the most significant limitations is that there was no opportunity to test the pattern design in a natural marine environment within the timeframe of this project. As a result, conclusions about the effectiveness of the design in enhancing biodiversity are still theoretical and require real-world testing for validation. Additionally, the proposed pattern design lacks a feature that can now only be created manually: crevices with varying widths within a single crevice. Ideally, the depth and width of a crevice should vary along its length to provide more complex habitats for marine life. Unfortunately, the pattern toolset that I created does not allow for this variation automatically.

8.3.2 | Marine life inhabitant categories

In my attempt to simplify my literature research, I categorized marine life into three inhabitant types (habitat builders, producers and regulators) that must be in balance in the reef ecosystem. While this approach helped me generalize conclusions for the ecological requirements, it potentially may be an oversimplification and not be entirely accurate from an ecology point of view. The categories are generalizations, and the needs of different species, even within the same category, can vary significantly, depending on their specific ecosystems. It will be very interesting to see with future field tests if my conclusions were correct or that I have falsely simplified them.

8.3.3 | Microalgae testing

One of the stakeholder requirements was that the Reefy logo be incorporated into the pattern design and so, the logo was used in the microalgae tests. This will allow Reefy to reference the results in future designs. However, as the design evolved, the orientation of the logo changed. And a different orientation likely influences the microalgae growth. While the results are still relevant, the orientation of the crevices plays a role in how microalgae grow, making this a limitation in interpreting the test results.

Another limitation was that the microalgae tests used the same 3D surface structure for all samples. These tests were primarily aimed at determining whether microalgae would grow in specific areas of the design, not at comparing different designs. While valuable lessons were learned from these tests, they did not fully explore the potential for optimizing different surface structures for microalgae growth. Moreover, the tools used for designing the pattern—such as Rhinoceros—are not freely available and may present a financial hurdle for a small startup like Reefy.

8.3.4 | Form liner

The form liner produced for this project was printed using a personal FDM printer, which has a limited bed size. This limitation meant that only small tiles (400x400mm) could be produced as depicted in Figure 113. Furthermore, the FDM printer introduced printing lines into the final product, which may affect the results of future field tests. While these lines could provide additional surface texture for small-scale organisms to settle in, they might also influence the overall marine growth in ways that need to be accounted for when analyzing test results.



Figure 113: *Example of a concrete tile producible with the form liner.*

8.4 | Ethics

8.4.1 | Effect on community structure

The ethical implications of this project largely revolve around its potential impact on marine life. One of the main concerns is the cascading effects that may result from the introduction of artificial substrates, such as this specific pattern design. Scientific literature often warns of the risks posed by artificial substrates, as they may facilitate the colonization of invasive and exotic species. These species, often introduced via ships, can dominate over the native species, especially if they lack natural predators in that new environment. This ecological imbalance can have far-reaching consequences, potentially altering entire ecosystems. A similar example has happened in the North Sea, where the Japanese oyster has moreover 'pushed out' the European flat oyster, in addition to the human overfishing activities. Which means that the European flat oyster is now a critically endangered species.

Despite these concerns, I believe that substrate design is not an exact science. Nature operates on its own terms, and it is challenging to predict how a specific artificial reef design will interact with marine life at a specific time and place. Each location is unique, and so are the potential outcomes of implementing an artificial substrate.

8.4.2 | Use of material

However, during the microalgae testing, I encountered another ethical concern: the use of concrete. In one test, I had sterilized small concrete prototypes before introducing them to the growth medium. But within two days, the microalgae in the test setup died, likely due to a chemical reaction between the concrete and the growth medium. This reaction caused visible clouding almost immediately after the prototypes were introduced but I was not aware of the effect it would have on the microalgae. From this experience, I learned that concrete prototypes need to be leached in water for at least a week before being exposed to marine life. This however raised ethical questions about the long-term impact of concrete in marine environments.

It is important to note that these microalgae tests were conducted in a very small amount of growth medium compared to the tiny ReefBlocks submerged in it. And only one microalgae was introduced per setup, which means that there is no possibility for survival of the fittest. And in contrast, in open water where the actual ReefBlocks are placed, this chemical reaction may be diluted so much that the effect is minimal and insignificant. Nevertheless, it is worth considering what effect concrete has on marine life, particularly on a microscopic scale. From the field tests that Reefy has conducted it is very clear that at meso (surface structure) and macro (over the entire ReefBlock) scale, the addition of a pattern design has a great positive impact and increases biodiversity significantly compared to the surrounding (natural) substrates. However, concrete is known to harden indefinitely, meaning that its chemical properties could continue to affect marine life long after the initial installation of an artificial reef. Therefore, it may be worth exploring alternative materials that have less impact on marine environments while keeping the structural integrity and durability, ensuring that artificial reef designs are as ecologically safe as possible.

Project Journey

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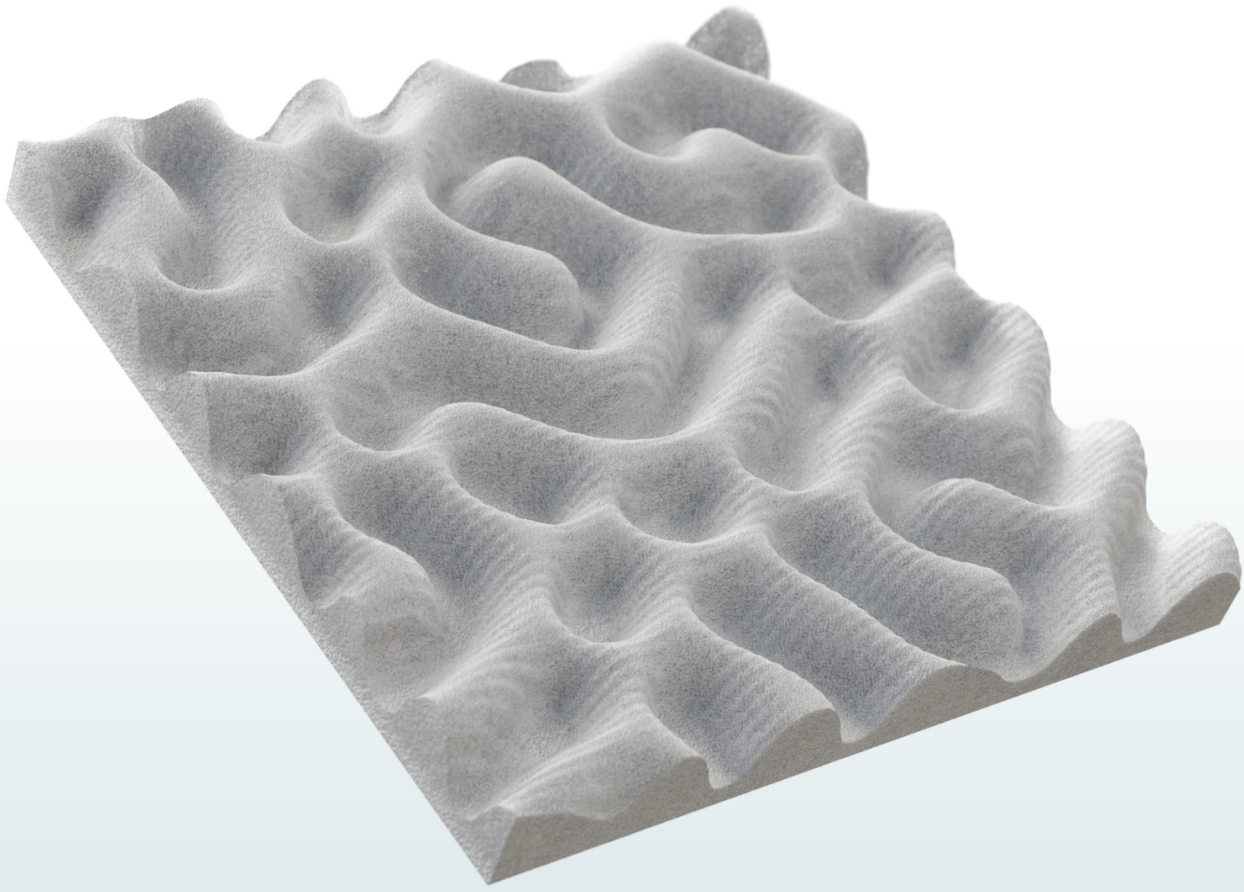

9.1 | Working towards my learning goals

9.1.1 | Learn parametric design

It was one of my ambitions to learn how to use a parametric tool in my design process. Prior to my graduation project I had a little bit of experience with Rhinoceros Grasshopper, which is why I was aware of its capabilities. However, I actually resented Grasshopper a little because I never understood it properly.

Throughout the course of the project, I had spent a lot of time understanding how to build a parametric model and how I could translate curves to grooves with varying widths that could be controlled within the Grasshopper tool. It took me a long time and many trials of different options to try to achieve that. Finally, I decided to let go of that idea and use the image sampler tool. This was not exactly the parametric model I had in mind, however, the image sampler tool worked really well and created the end result that I was looking for. In the end, I am happy that I made that decision, as the choice for the image sampler resulted in the use of generative art. And as presented in this report, it is the power of the combination of generative art with the parametric model that has become one of the most valuable deliverables for Reefy.

Despite that I was not able to achieve the exact use for the parametric model, in the end, I do feel like I have achieved my learning goal as I learned a lot about the benefits of using such a design tool. Being able to change your starting point without the need to reapply all the consecutive steps works really great during an iterative design process and saves so much time. Now that I understand Grasshopper, I will definitely use it again in the future. While I was making the 2D image in Photoshop, I wished I could also apply the same logic to make that process even quicker and mainly more organized.

9.1.2 | Conduct biolab test

Conducting the microalgae tests in the Biolab was a bit of a rollercoaster, but despite that, it was a really fun experience and in the end all was well and the test showed great results. But at the beginning of my project I had totally underestimated the amount of time I would need on preparing for the final test, as I struggled with making decisions. Therefore, the planning to officially start the microalgae test kept shifting forward throughout my project. Because of the unanswered questions about whether the algae would survive and if there would be any visible results at all, I had to conduct a few additional smaller tests.

Reflecting on the time management for these tests, I definitely should have conducted them earlier on, as the first small test I did killed all the microalgae involved. This required me to adapt and conduct two more small tests which helped me understand that the concrete prototypes must be 'leached' in water for over a week, before introducing them to a microalgae culture. All of this took place over the course of multiple weeks, as microalgae need time before results are visible. The leaching conclusion also meant that at least two additional weeks were needed to prepare the prototypes for final testing, which delayed the planning even more.

The entire setup for the test had to be 'designed' and built, including the entire pump installation and electronics. Fortunately, the supervisor from the IDE Biolab, Joren Wierenga, has a lot of knowledge and was willing to think along with me, and helped me so much with setting up the tests. So, I would like to give him a special thanks for all the guidance and help he has given me.

By growing the microalgae over the course of multiple weeks, I gained experience working with the microalgae, their growth behavior and the tools that are used in a biolab to grow them. Which really helped me along, once I started the official testing.

I learned that you move very slowly in a lab, because you always have to think of the order of things: especially when adding more medium to your microalgae culture. The medium must remain sterile and not be contaminated with your microalgae culture. That also means that I had to be very careful and so I had to move slowly. I did notice that I became better and faster at this process, as I felt more and more confident and familiar with the tools.

9.2 | Working to the project goal

From the start, the goal of this project was very clear, allowing me to focus on the finer details of what the design should include and what it should look like. This clarity also gave me the time and space to explore and achieve both of my learning goals.

Time management is often an area of difficulty for me during projects. Throughout my project I had ups and downs in how I distributed my time across different activities, and at times I may not have worked as effectively as I could have. The subject of this project interests me a lot, and so my research phase was very extensive. I always have a tendency to spend too much time gathering more information, which at times caused me to lose track of what was most relevant, and also left me feeling overwhelmed.

Perfectionism turning into indecisiveness also played a role, where I sometimes tended to spend more time analyzing than taking action. At the basis of this was a feeling of uncertainty what to do next and how to approach the project. Luckily I have supportive friends and family around me who provided me with a sympathetic ear throughout the process which helped me gain an outsider perspective, and with special thanks to my boyfriend who has taken on that role a lot and helped me so much, and so I want to thank them for their great support throughout my academic years.

The weekly meetings with my supervisors, Joana Soares Martins and Caroline Kroon, were essential in keeping me on track and motivated to act, especially in those early stages of my project. These meetings forced me to weekly digest my insights and collected information into concise summaries, which in the end has led to very useful conclusions for my project. And so, I want to thank my supervisors for their weekly availability, as it made me feel well-supported, even during moments of uncertainty about how to proceed.

Along with the additional support from the mentors from Reefy, Daan Houtzager and Leon Haines, who helped me clarify the important stakeholder, ecological, and production requirements. And I want to thank them for their guidance and readily available feedback throughout the course of this project.

As my methods evolved during the project, so did my understanding of time management. Initially, I thought selecting the 2D image would be a quick task, and my primary focus should be on creating the 3D surface with the parametric tool. However, as my understanding of the parametric model evolved, I realized the importance of the 2D image, which drives the possibilities in three-dimensional space. This shifted my perspective and became the key aspect of my project.

The major breakthrough of this project was definitely the day I found the generative art method. Before this, my process to create pattern designs was very slow, as I created them by hand in Adobe Photoshop. Whenever I wanted to try something out at ReefBlock scale, it took a long time before I went from an updated design direction to a fully prepared 2D image for Grasshopper. And so this process did not allow for quick iterations at all. But, the newly found method of generating similar designs in Photoshop actually created the complete opposite challenge: I was able to make new designs so quickly, that I could also very quickly lose sight of what I had already tried, and what worked and what didn't work, if I did not pay attention to document my steps along the way.

Finally, the need for additional time to complete the microalgae testing led to a three-week extension for my project. This extra time proved worthwhile, as the tests ultimately produced great results, which I am very pleased with.

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Appendices

A. Project brief
B. Solutions benchmarking overview
C. List of requirements
D. Aesthetics survey
   - Aesthetics survey results
E. Preliminary microalgae tests
   - Microalgae test 1
   - Material test
   - Microalgae test 2
F. Microalgae test documentation

A | Project brief

TU Delft

DESIGN FOR our future

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	van den Boogaart
Initials	M.L.
Given name	Martine
Student number	4659287

IDE master(s)	IPD ✓	DfI	SPD	
2nd non-IDE master				
Individual programme *(date of approval)*				
Medisign				
HPM				

SUPERVISORY TEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Joana Soares Martins	dept./section	Mechatronics/Materialising Futures
mentor	Caroline Kroon	dept./section	Design for Sustainability/DfS
2nd mentor	Daan Houtzager		
client:	Reefy B.V.		
city:	Delft	country:	the Netherlands
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in by the Chair of the supervisory team

Sign for approval (Chair)

Name | Date | Signature

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Martine van den Boogaart **Student number** 4,659,287

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Designing a Surface Texture in a Pattern for Biodiversity Enhancement on Artificial ReefBlocks

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

In the last three decades coastal ecosystems, such as coral reefs, have been declining at a fast rate due to e.g. climate change all around the planet. Large reefs play an important role in reducing wave energy, before waves reach coastlines. Right behind and in between reefs the water is calmer, also allowing oyster reefs and seagrass fields to develop. And together, these ecosystems are vital for sustaining marine life.

The company Reefy has created the first modular artificial reef that takes on the natural breakwater function of reefs. By means of their "ReefBlock" (Image 1) they are able to effectively dissipate wave energy for coastal protection, while simultaneously providing a substrate and habitat to support a complex coastal ecosystem.

Targeted buyers of the ReefBlocks are municipalities and resorts all over the world that want to protect their coastlines for e.g. beach and asset protection, and regenerate reefs to preserve local ecosystems and help attract tourists for diving. This means that the targeted areas range from warm to temperate climates, with varying coastal ecosystems.

The structure of the ReefBlock is based on technical requirements for stability and modularity, while providing a home to marine animals. Whereas the surface area creates the opportunity to provide a foundation for micro- and macroorganisms, by means of a surface texture that can be enhanced for boosting biodiversity.

Aside from the functional opportunity, there is also an opportunity to create an attractive product for the targeted customer stakeholders: to play with the aesthetics of the artificial ReefBlock over time. From newly placed to a developing biodiverse ecosystem. However, it cannot be completely controlled and predicted how nature will slowly develop itself over time. Since it depends on the local environment and circumstances if a beautiful and biodiverse reef is formed.

→ *space available for images / figures on next page*

introduction (continued): space for images



image / figure 1 Reefy's ReefBlock: the size relative to its designers and with the current surface textures [1 & 2].



image / figure 2 Algae growth over time on the current ReefBlock in a marine context.

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Because of the symbiotic nature between reefs and marine life, it is vital to attract a variety of local species to maintain an ecosystem. To support that, a textured surface can attract certain species on a small scale by creating different abiotic conditions. Currently, the ReefBlock has two wave-like textures (Image 1.1 & 1.2). Adding a surface texture seems to enhance biodiversity compared to a smoother surface, on which mostly microalgae cultivate (Image 2). However, it has not yet been explored to design a custom surface texture that specifically combines the needs of ecosystems in both warm and temperate climates and aesthetic wishes to attract relevant stakeholders, applied to the specific use case of the ReefBlock.

Therefore, my assignment is to research the ecological function requirements and stakeholder wishes that together determine the surface texture aesthetics; to validate the effectiveness of the necessary global abiotic conditions that support biodiversity; and to design the textured pattern for a production mold component. The abiotic conditions cannot be validated in a natural environment within the time frame of the project. However, the TU Delft has access to microalgae strains, which if grown on the designed surface, can be used to test certain abiotic conditions much faster in a controlled environment. Hypotheses can be formulated about the predicted development of bio-colonization on the surface texture and the created unique aesthetics of the developing ecosystem on the ReefBlock.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Support a biodiverse ecosystem on the surface area of an artificial reef block, by designing a production mold formliner that creates a surface texture with a variety of abiotic conditions and a desired aesthetic pattern.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

With this graduation project I aim to contribute to the research field of marine coastal ecosystems, by researching and mapping the needs of marine life at the meta (climate), macro (symbiotic relationships), and micro (species) levels. By comparing these needs and drawing inspiration from biomimicry and existing knowledge, I will be able to formulate the general abiotic conditions that the surface texture on ReefBlocks must provide, to effectively enhance marine biodiversity in different climates. These abiotic conditions can be translated into a list of ecological requirements that define the parameters of the surface texture. And those parameters can be explored using a Material Driven Design (MDD) method and microalgae as test subjects.

By means of talking to the targeted customer stakeholders I aim to collect and understand valuable opinions, needs and wishes with regards to a holistic view of the textured surface as a (living) pattern. The overall achieved aesthetics of the ReefBlock pattern influences its marketability and cultural meaning in a larger context.
Finally, I will combine the textural and pattern properties into one coherent design that is producible in a mold formliner, by utilizing a computational design tool.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	18 apr 2024
Mid-term evaluation	13 juni 2024
Green light meeting	6 sept 2024
Graduation ceremony	8 okt 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	20
Number of project days per week	5,0

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This project allows me to design a novel marine biodiversity enhancement texture, with potential global implementation and impact. This potential impact is a significant motivator for me to take on this challenge. Despite lacking prior experience in designing for marine life, I am supported by Reefy's in-house biology expertise and have enlisted a Chair who is a biologist familiar with microalgae. Moreover, Reefy has access to a network of relevant experts and I anticipate reaching out to various experts to gather the ecological requirements and understand the interdependencies thoroughly.

In this project, I aim to showcase a structured proactive approach. Initiating creation, testing, and iteration early on. While conducting literature reviews and identifying commonalities, I will simultaneously try conducting quick tests to gain insights using MDD. I have the tendency to over-research, so I have enlisted a Mentor who can help me maintain focus and make decisions. Additionally, I want to develop skills in setting up performance tests using living organisms, such as microalgae strains. In collaboration with my Chair and Reefy, these tests will be set up in a controlled environment at the TU Delft campus.

Furthermore, I aim to expand my 3D CAD modeling skills by exploring the computational design tool Grasshopper in Rhinoceros, to develop a parametric model to incorporate the ecological requirements. This model should facilitate me in quick exploration, testing, and the creation of a distinctive and organically textured pattern.

B | Solutions benchmarking overview



ARC Marine - Reef Cubes

High intertidal | Low intertidal | Unspecified

Effective

Measured effects:
An aggregated finish seems to create a great enough surface roughness for a variety of marine life to attach to. Their best image shows quite a few mussels (habitat builders) and about 12 sea stars (habitat regulators) that are munching on the mussels and much of the surface is covered in a variety of habitat producers.
Visual elements:
The Reef Cubes are hollow cubes with large holes. They have one much more elaborated design with a complex surface structure resembling an ammonite with abstract art style. However their image that shows the most biodiversity is with smaller cubes with no additional design and an aggregated surface finish.

Casting | Concrete

Aggregated | Holes | Dome



Archireef

Subtidal | Habitat builders

Adequate

Measured effects:
They also use seeding to boost the presence of specific habitat builders; in the one clear image that shows marine life around the tiles, the seeded corals seem to have grown and further more some other (smaller) habitat builders like barnacles and tube worms are visible and a cuttlefish that feeds on them.
Visual elements:
They based their crevice design on biomimicry of hard corals and oysters, which seems similar to the pattern of brain corals. The holes in the bottom grid allow for sediment to fall through.

3D printing | Ceramics

Fine | Layers | Grooves | Crevices | Overhangs

Holes



Art installation reefs

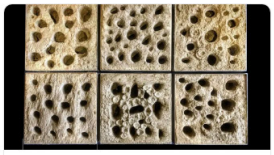
Subtidal | Unspecified

Adequate

Measured effects:
No research or specific website is found that describes measured effects, but the header image shows the potential of biodiversity and specifically, habitat builders and producers. Only most examples do not specifically show sheltering areas for habitat regulators.
Visual elements:
Many of the art examples implement a variety of overhangs, holes and ridges in a more random manner; which benefits complexity and heterogeneity.

Sculpting | Ceramics

Grainy | Ridges | Overhangs | Towers | Tunnels



Artecology - Intertidal Habitat Panels

Low intertidal | High intertidal

Adequate

Measured effects:
Unknown (no examples), however the use of pits proven to be colonized by small mussels and barnacles in intertidal zones. Obviously, results depend on the location.
Visual elements:
Varying holes sizes, that will likely support varying inhabitant sizes. Its visually similar to a bee hotel (that they also sell)

Sculpting | Ceramics

Grainy | Coarse | Pits | Crevices



Artecology - Vertipools

High intertidal | Mid intertidal | Unspecified

Adequate

Measured effects:
The implemented recesses seem too shallow to host anything other than macro- and microalgae. The rockpools may provide a home for more organisms, as they also have a more complex interior.
Visual elements:
Like a flower pot with a beeswax-like texture on the outside. Separated wall hanging element; in the interior it has a more complex structure.

Sculpting | Ceramics

Grainy | Grooves | Pits | Overhangs

Multi-layered | Rock pools



Bishop at el. (2022) - Living Seawalls (Reef Design Lab)

Low intertidal | Mid intertidal | High intertidal

Unspecified

Effective

Measured effects:
Most species detected in the crevice and rockpool designs;
Visual elements:
Mimicking microhabitat features of intertidal rocky shores, so mainly representing rock including the functionalities.

Casting | 3D printing | Concrete

Fine | Grainy | Crevices | Pits | Holes

Rock pools



Blue Regeneration - BioRock

Subtidal | Habitat builders

Effective

Measured effects:
The low-voltage on the dome is what they claim to be effective; likely, the combination with seeding has the biggest influence.
Visual elements:
Large dome of metal, like a cage; creating instant height to the emerging reef.

Joining | Metals

Smooth | Layers | Dome



Bone et al., 2022 - Vertipools (Artecology)

Mid intertidal | High intertidal

Adequate

Measured effects:
Retained sediment within eco-engineered features on hard ACSs can create habitat for benthic assemblages and may even have more benthic species than the local mudflats (but due to limitations of the study, this comparison is probably unfair).
Visual elements:
Representing like a simple hanging flower pot, but mimicking a rock pool in functionality.

Casting | Concrete

Fine | Rock pools



Callaway (n.d.)

High intertidal | Unspecified

Ineffective

Measured effects:
Location too far from the water; the only inhabitants were in between and on the sides of the tiles, where deeper 'crevices' are deeper and more protective.
Visual elements:
Using Reckli form liners, and one custom: visually using benthic bivalves, yet not functionally

Casting | Concrete

Fine | Grainy | Coarse | Grooves | Ridges



Car tire reefs

Subtidal | Unspecified

Harmful

Measured effects:
Later on determined to be detrimental to marine life, as the tires slowly degrade, dragged across the sea floor, subjected to sedimentation and generally don't seem to support many marine organisms.
Visual elements:
Literal rubber car tires, thrown in the sea. These hollow tires do create deep overhangs.

Casting | Polymers

Fine | Tunnels



ECOncrete - Armor Blocks

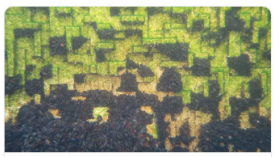
Subtidal | High intertidal

Adequate

Measured effects:
The only found examples with marine life are high in the intertidal zone; and there only habitat producers are visible. No clear images of the marine effects in the subtidal zone. Likely the multi-layeredness helps to house small habitat regulators. And the ridges likely support habitat builders without additional layers; as the water flow/light availability may be too low for them behind there. The rockpools hold water in the intertidal zone and that allows mainly habitat producers and also other marine life to remain cool and moist above water.
Visual elements:
Their designs allow for the attachment of additional layers of other materials, such as metal grates. Their designs mostly represent height maps 'carved out' in steps. On the horizontal plane these 'steps' create rockpools that can hold water in the intertidal zone.

Casting | Concrete

Fine | Ridges | Overhangs | Multi-layered



ECOncrete - Wall Panels

Subtidal | Mid intertidal | Habitat builders

Adequate

Measured effects:
In the best visible images, mainly mussels (habitat builders) start growing underneath the ridges and grow over the ridges when they grow over each other. Barnacles (habitat builders) and habitat producers are visible on the flat outsides of the patterns, as well as on top of the sharp ridges.
Visual elements:
They have both shallow 'carved out' patterns and short protruding tower patterns, that both create sharp ridges underneath which habitat builders can attach.

Casting | Concrete

Smooth | Ridges | Towers



EcoReefs

Subtidal | Habitat builders

Effective

Measured effects:
It seems the design is meant to protect the seeded corals with their own defence structure; based on the thumbnail image, it seems to effectively protect the coral; but further substrate effects are unknown.
Visual elements:
Abstract representation of he branching Staghorn coral.

Casting | Ceramics

Branches (fractals)



Encrustations (Naylor's tiles)

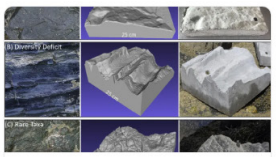
High intertidal | Habitat builders | Subtidal

Effective

Measured effects:
The alternating direction of the shallow grooves enhance the likelihood of uniform settlement by cyprid barnacles. Clearly barnacles prefer settling in between elevations.
Visual elements:
Visually representing an abstraction of barnacles in a repeating pattern. This tile was fully dedicated to barnacle colonization.

3D printing | Ceramics | Bio-compounds

Grainy | Layers | Grooves



Evans at al. (2021) - Ecostructure Project

Mid intertidal | Unspecified

Adequate

"Replicating natural topography on marine artificial structures – A novel approach to eco-engineering"
Measured effects:
Similar recruitment was found with regards to species richness. They only mention that limpets were found in pooled and shaded channels, no clear results on other inhabitants were reported, as the article is more about the technique used. The removed rare species did not return on the same design.
Visual elements:
Literally took 3D scans of "the best" rock segments, based on the richness of species, presence of rare (rocky reef) species.

3D printing | Casting | Concrete

Grainy | Coarse | Crevices | Ridges



ECOncrete - Armor Blocks

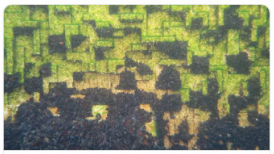
Subtidal · High intertidal

Adequate

Measured effects:
The only found examples with marine life are high in the intertidal zone; and there only habitat producers are visible. No clear images of the marine effects in the subtidal zone. Likely the multi-layeredness helps to house small habitat regulators. And the ridges likely support habitat builders without additional layers; as the water flow/light availability may be too low for them behind there. The rockpools hold water in the intertidal zone and that allows mainly habitat producers and also other marine life to remain cool and moist above water.
Visual elements:
Their designs allow for the attachment of additional layers of other materials, such as metal grates. Their designs mostly represent height maps 'carved out' in steps. On the horizontal plane these 'steps' create rockpools that can hold water in the intertidal zone.

Casting · Concrete

Fine · Ridges · Overhangs · Multi-layered



EOncrete - Wall Panels

Subtidal · Mid intertidal · Habitat builders

Adequate

Measured effects:
In the best visible images, mainly mussels (habitat builders) start growing underneath the ridges and grow over the ridges when they grow over each other. Barnacles (habitat builders) and habitat producers are visible on the flat outsides of the patterns, as well as on top of the sharp ridges.
Visual elements:
They have both shallow 'carved out' patterns and short protruding tower patterns, that both create sharp ridges underneath which habitat builders can attach.

Casting · Concrete

Smooth · Ridges · Towers



EcoReefs

Subtidal · Habitat builders

Effective

Measured effects:
It seems the design is meant to protect the seeded corals with their own defence structure; based on the thumbnail image, it seems to effectively protect the coral; but further substrate effects are unknown.
Visual elements:
Abstract representation of the branching Staghorn coral.

Casting · Ceramics

Branches (fractals)



Encrustations (Naylor's tiles)

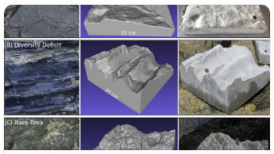
High intertidal · Habitat builders · Subtidal

Effective

Measured effects:
The alternating direction of the shallow grooves enhance the likelihood of uniform settlement by cyprid barnacles. Clearly barnacles prefer settling in between elevations.
Visual elements:
Visually representing an abstraction of barnacles in a repeating pattern. This tile was fully dedicated to barnacle colonization.

3D printing · Ceramics · Bio-compounds

Grainy · Layers · Grooves



Evans at al. (2021) - Ecostructure Project

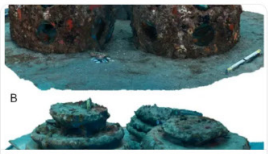
Mid intertidal · Unspecified

Adequate

"Replicating natural topography on marine artificial structures – A novel approach to eco-engineering"
Measured effects:
Similar recruitment was found with regards to species richness. They only mention that limpets were found in pooled and shaded channels, no clear results on other inhabitants were reported, as the article is more about the technique used. The removed rare species did not return on the same design.
Visual elements:
Literally took 3D scans of "the best" rock segments, based on the richness of species, presence of rare (rocky reef) species.

3D printing · Casting · Concrete

Grainy · Coarse · Crevices · Ridges



Hylkema et al. (2020) - ft. Reef Ball Foundation (a comparison of Reef balls, Layered cakes & Rock piles)

Subtidal · Habitat regulators

Adequate

Measured effects:
Layered cakes performed better in terms of fish abundance and biomass than the other types, *suggesting that crevices and grooves have a positive effect, due to their smaller sized 'cave' habitat formation.*
Visual elements:
Overall all these designs are almost like a representation of a large circular rock. The layered-cake design has large overhangs, the reef balls are an empty dome with holes that create smaller overhangs and the pile of rocks creates more smaller-sized nooks and crannies in between.

Casting · Concrete

Fine · Holes · Overhangs · Tunnels · Multi-layered



Kosová et al. (2023) - BioGeo Ecotiles

High intertidal · Habitat builders · Habitat producers

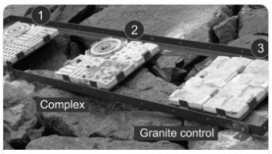
Habitat regulators

Effective

Measured effects:
Combination of mm and cm-scale structural features and barnacle biomimicry creates the high habitat heterogeneity missing on rock armour and seawalls, with a larger effect on sessile species than on mobile species.
Visual elements:
Mimicking living and dead (hollow) barnacles, as well as rock surface crevices and ridges. But, visually very unappealing.

3D printing · Casting · Concrete

Fine · Coarse · Grooves · Crevices · Pits · Ridges



Loke & Todd (2016)

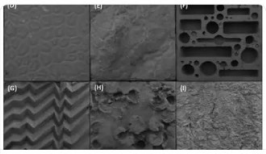
Low intertidal · High intertidal · Habitat regulators

Adequate

Measured effects:
Structural complexity and component type increase intertidal biodiversity independently of area. Pits, grooves and towers supported the greatest richness; pooled water hosts greater biodiversity in the intertidal.
Visual elements:
Simple abstract geometries, for each one simple and one more complex design. Use of circular crevices, square pits and towers and ridges.

CNC machining · Casting · Concrete

Smooth · Pits · Grooves · Ridges · Towers



MacArthur et al. (2019)

Mid intertidal · High intertidal · Unspecified

Effective

"Maximising the ecological value of hard coastal structures using textured formliners"
Measured effects:
The addition of **microhabitats at the scale of 10–30 mm in depth and widths**, improves species richness and abundance on hard vertical coastal defences by providing habitat that would otherwise have been absent.
Visual elements:
Varying greatly, they used 160 samples (150x150mm).

Casting · Concrete

Fine · Grainy · Coarse · Aggregated · Grooves · Crevices · Pits · Ridges · Overhangs



Moreef

Subtidal · Habitat builders · Grazers · Predators

Adequate

Measured effects:
The smoother surface texture allows mainly for biofilm formation, and the larger design elements for shelter for larger animals; the tunnels allow refuge for an octopus and also soft reef builders (that are predators) and the smaller holes for urchins or for seeding corals.
Visual elements:
Like a layered cake; only on centimeter-scale, no additional surface texture; only addition of a few pits per unit and overhangs due to the tunnels (does not seem designed for storm conditions).

Casting · Concrete

Smooth · Pits · Holes · Tunnels



Oyster Castles

Low intertidal · High intertidal · Habitat builders

Effective

Measured effects:
It seems very effective for oyster recruitment with algae mainly at the top; but the complex tunnel system allows for oysters to settle in higher numbers as well as barnacles on the sides of the blocks.
Visual elements:
The name refers to their tower-like structure, that allows for a more complex looking, hollow brick with a varying wall height.

Casting · Ceramics



Paalvast (2011)

High intertidal · Low intertidal · Unspecified

Adequate

Measured effects:
Geometrical structures have proven to be essential for the settlement and refuge of mussels (habitat builders) and periwinkles (grazers). Mussels mainly grew in the horizontal crevices and pits on the vertical plane and in the rockpools in the horizontal plane; For barnacles surface texture does not have a significant effect, but vertical surfaces had a higher abundance of barnacles than horizontal. Fine and middle fine texture promotes a fast colonization of macroalga; however, after a couple of months there is no difference with the smooth surface texture.
Visual elements:
This was a research about design features with different characteristics, and how these influence the growth of marine life. Abstract visual elements were used: horizontal and vertical crevices and pits with varying sizes; as well as three different surface roughnesses.

Casting · Concrete

Smooth · Fine · Coarse · Crevices · Pits · Rock pools



Plymouth University - Bio Blocks

High intertidal · Mid intertidal

Ineffective

Measured effects:
Unclear, only visual with marine life shows algae only. Seems quite ineffective, but the shown locations are neither inter- as subtidal.
Visual elements:
Large cube with smooth to fine surface texture, addition of shallow and regular placed pits and small crevices

Casting · Concrete

Smooth · Pits · Crevices · Rock pools



Portsea - Wall Panels

Mid intertidal · High intertidal

Adequate

Measured effects:
No images or research was found that showed the effects of this design on marine life settlement. Likely, the crevices and pits will effect habitat builder settlement as well as habitat regulators that seek refuge. However the sizes of the square overhangs is very large and open for the smaller-sized marine life, perhaps mainly the sides will be colonized. The shallow ridges may also affect habitat builders, but mainly algae will more likely grow over the areas in between.
Visual elements:
Very abstract rectangular shape cutouts with a few circular pits that 'break' the horizontal ridges. No clear design vision, they applied similar design features to Paalvast's (2011) research setup.

Casting · Concrete

Smooth · Crevices · Pits · Ridges · Overhangs



Potet et al. (2021)

Subtidal · Habitat builders

"Which concrete substrate suits you? Ostrea edulis larval preferences and implications for shellfish restoration in Europe"
Measured effects:
Weak effects of material formulation but strong effects of micro-topography at mm scale (close to larvae size); Strong preference for sidewalls and in pits or valley bottoms.
Visual elements:
Using Reckli form liners (!), with a variety of depths and profiles.

Casting · Concrete

Fine · Grainy · Aggregated · Grooves



Reef Ball Foundation - Layered Cakes

Subtidal | Habitat builders | Habitat regulators

Effective

Measured effects:
Mainly the shelter area of the top overhang seems to be very effective. The overhang below that has more space in between and visibly hosts less marine life. Uncertain which corals are seeded or not at all.
Visual elements:
From larger layer below to smaller layer on top; like a layered cake or a spiral staircase, which creates large overhangs, casting shadow below.

Casting | Concrete

Grainy | Overhangs | Tunnels



Reef Ball Foundation - Reef Balls

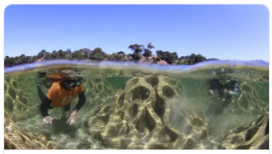
Subtidal | Habitat producers | Habitat regulators

Ineffective

Measured effects:
Seem to provide mainly shelter for larger habitat regulators, but fine surface texture allows mainly algae (habitat producers) to grow over the surface.
Visual elements:
Hollow round concrete balls with sort of triangle cut-out holes; chained to the seabed and no specific surface texture.

Casting | Concrete

Grainy | Dome | Holes



Reef Design Lab - EMU

Subtidal | Low intertidal | Unspecified

Effective

Measured effects:
Their main purpose is to defense against coastal erosion, while enhancing marine habitat. Additional images show that the 3D-printing layers allow habitat builders to settle in the grooves; and the larger holes in the structure may provide refuge for larger habitat regulators.
Visual elements:
The visual aesthetic reminds me of a sort of flower with the hole pattern or like a jellyfish or mushroom due to the overall shapes.

3D printing | Concrete | Bio-compounds

Layers | Aggregated | Grooves | Holes | Tunnels

Rock pools



Reef Design Lab - Living Sea Walls

Mid intertidal | High intertidal | Unspecified

Effective

Measured effects:
Used in a couple of scientific papers, and seem to increase biodiversity very well. Clearly, in the created pits more diverse marine life is seeking shelter; among which oysters (habitat builders) and a few grazing habitat regulators; yet on the layered surface texture many barnacles (habitat builders) seem to settle; as well as a few algae (habitat producers).
Visual elements:
They have different designs, but all of them are based on biomimicry, with inspiration drawn from: mangrove roots, (dead) coral, oysters, sponges, honeycombs, rock ridges and rock pools. The tiles have a flower-like (hexagonal) shape and their mold is 3D printed, which is visible in the concrete casts and creates a layered surface texture. With some of their designs the design features are visually overlapping, which creates a more complex aesthetic with multiple 'layers' and pits in between.



Reefy - ReefBlock

Subtidal | Low intertidal | Habitat builders

Habitat regulators | Habitat producers

Effective

Measured effects:
The main effect for biodiversity is measured in the deeper structure (~3cm deep). The shallow pattern is mainly occupied by algae turf and the deeper pattern with all kinds of habitat builders as well as refuge for habitat regulators
Visual elements:
Mainly waves in a horizontal orientation with a visual emphasis on the holes in the middle with a straight continuous strip around the ReefBlock.

Casting | Concrete

Smooth | Crevices | Ridges | Tunnels



Rigs-to-Reefs

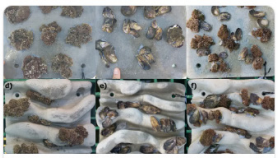
Subtidal | Unspecified

Effective

Measured effects:
Despite the smooth surface finish of metal, the 'overhangs' created by the construction of rigs allows a variety of habitat builders and producers to grow around them. In many images it is visible that many habitat regulators live in and around these rig reefs from very small to very large.
Visual elements:
The design of rigs is functional and based on construction requirements, which is similar to a transmission tower. However visually this means it has horizontal, diagonal and vertical overhangs that cross each other.

Joining | Metals

Smooth | Overhangs



Ushiama et al. (2019) ft. Reef Design Lab

Low intertidal | Mid intertidal | Habitat regulators

Predators | Habitat builders

Measured effects:
Fish interact more with the seeded tiles with developed fouling communities. Seeded tiles have significantly higher sessile species richness, also inside crevices significantly higher than on ledges.
Visual elements:
Irregular ridges of varying sizes, representing an eroded rocky topography.

3D printing | Casting | Concrete

Fine | Crevices



Vehicle wrecks

Subtidal | Unspecified

Effective

Measured effects:
If the vehicles were stripped of any harmful chemicals before sinking, these structures create complex habitats for a variety of marine life.
Visual elements:
Either unintended or deliberate wrecks from ships to old tramways or school busses.

Metals | Wood

Smooth | Tunnels | Dome | Multi-layered

Overhangs

C | List of requirements

Project Part	Nr.	Requirement	Notes
Marine life Pattern Design			
		Microhabitats must be distributed evenly over the surface area of the pattern.	For the biodiversity index
		Concentration for seaweed promotion must be mainly at the top side of the pattern.	Seaweeds can keep what is underneath them moist when above water.
		The pattern provides the design features of crevices and pits.	A complex habitat; how much does 'high number' mean exactly? How do I judge what number is correct (together with Leon).
		The pattern provides a great variety of habitat sizes.	A heterogene habitat; how many different sizes exactly and for 'who'?
		The pattern provides shadowed areas.	
		The pattern provides hiding spots for mobile habitat regulators (5-50mm)	
		Surface area must be maximized by complex shapes adding depth/height.	
		The pattern provides 'lee' zones where waterflow is low.	
		The pattern is divided in three zones with regards to depth, for each type of ecosystem engineers.	The three types of ecosystem engineers are: habitat builders, habitat producers and habitat regulators. The producers require most sunlight, and are expected to grow fastest and dominate the most lit 'top level'. Many builders require sunlight and access to water flow.
		The pattern is divided in a gradient from less dense at the top to more dense at the bottom.	
		A smooth suface texture accounts for habitat suppliers high lit areas.	
		A grooved texture accounts for habitat builders in medium towards high lit areas.	Representing 3D printed layers as an inspiration
		Pits in varying sizes, equally distributed over the surface	
		Focus of vertical crevices on the top half of the pattern	
		Focus of smoother textures (eroded, like fossilized coral) on the top half	
		Allowing all reef inhabitants (habitat builders, producers and regulators) to compete in an equal matter, distributed over the ReefBlock.	
		The pattern is designed for daily conditions, not considering the extreme storm conditions.	
		The included reef inhabitants interact with hard substrates in the photic zone	
		The applied surface texture for habitat builder larvae is most present at depths of 10-20mm (-20 ≤ x ≤ -10 mm)	
		The pattern integrates pits large enough for coral plugs or direct coral seeding.	This allows for seeding of mature habitat builders when placing the ReefBlocks in a marine environment
Aesthetic Pattern			
Wishes / design criteria		The pattern visually represents a lobed brain coral.	Since this is a flagship "specie" that represents ecosystems and the restoration of marine life.
		The pattern is based on reaction-diffusion, as found naturally in brain corals.	
		The pattern takes into account the tunnel shapes in the ReefBlock.	Make it look like it is designed for the ReefBlock
		The pattern is based on a 2D black & white image	White equals depth = 0mm and black euals depth = 30mm
		The 2D image is adapted for varying depths by use of gray values.	Gray equals depth values between 0-30mm
		The pattern has the Reefy logo incorporated.	For brand integration
		The pattern helps to visually break the rectangular shape of the ReefBlock	
		The pattern visually looks like it was designed specifically for the ReefBlocks	
		The pattern looks visually balanced	Distribution of design elements
		The pattern visually fits in a marine context	
		The pattern is adjustable to fit an 800x2800mm rectangle, an 800x800mm and a 400x400mm square.	
		The pattern includes a smooth transition towards the sides that have a depth of 0mm.	This makes sure that there will be no sharp and weird edges, and ensures a better visual intergration with the ReefBlock
		The pattern is perceived as aesthetically pleasing by "all"	
Producibility			
		The same pattern is applied to all sides of the ReefBlock	
		Every 1cm in depth of a design element must be accompanied with at least 1cm in width.	This rule of thumb will assure better form liner durability.
		The form liner (recesses and protrusions) can be released perpendicular to the surface.	Due to the production technique and form liner construction.
		All recesses and protrusions must have a slight inward draft angle.	Rule of thumb: the more draft angle, the easier it releases from the form liner. Up to 15-20mm deep the draft angle can be 90°, but a slight draft angle is better.
		The base thickness of the form liner is 8mm.	The same as the used Reckli 'Corse' formliner.
		The deepest crevices have depths of 0-30mm. (-30 ≤ x ≤ 0 mm)	Similar to the Reckli 'Corse' formliner.
		The highest protrusions are in line with the ReefBlock outside.	Similar to the Reckli 'Corse' formliner.
		The form liner has no inward undercuts.	
		The form liner has no overhangs.	
		All edges and corners are rounded for smooth transitions.	Because this is less prone to break off than sharper edges.
		The price range of the new form liner should be: €400-€500.	Similar to the current design.
		A section of the mother mold (for producing the form liner) is used to create the pattern design on the short side of the ReefBlock.	To reduce production costs of making the 'mother form liner'
		A depth of 0mm is equally distributed over the pattern surface area.	To ensure stable stacking of ReefBlocks and avoid pressure points
		The pattern design must fit the dimensions of the designated area on the ReefBlock.	

D | Aesthetics survey



Designing a pattern for enhancing marine biodiversity on artificial reefs

This survey is anonymous, can be finished under 3 minutes and helps me collect some insights for my graduation project! This project is commissioned by the TU Delft and the company Reefy.

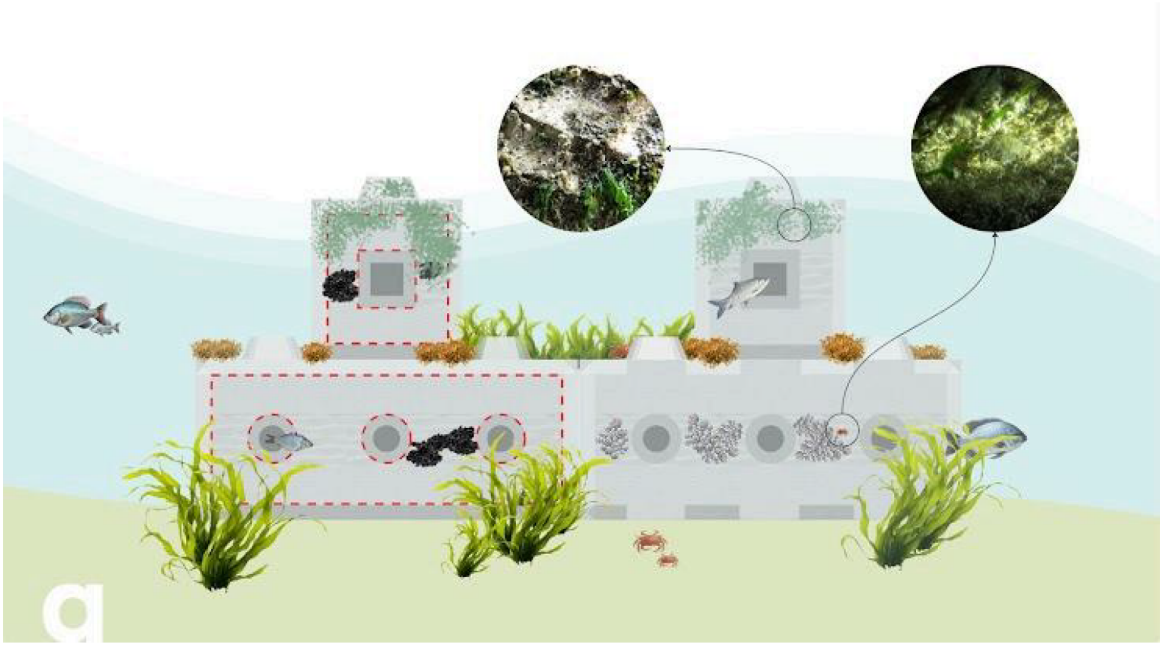
Artificial reefs are human-made structures that provide shelter for diverse marine life, just like natural coral reefs (see header image).
The company Reefy has created a modular artificial "ReefBlock" for which I have designed 3 patterns that can enhance biodiversity on the sides of the ReefBlock (see image a, red outlined areas). Each pattern creates a 3D depth structure where marine life can shelter in or around.

The purpose of this survey is to collect and understand the general public's view on the overall aesthetics of three proposed pattern designs.

Niet gedeeld

* Verplichte vraag

Image a: Visual representation of ReefBlocks in a natural environment, with the red outlined areas indicating where the pattern design will be implemented.



My age is: *

Jouw antwoord

I have seen a natural reef in real life under water: *

- ○ Yes
- ○ No

The inspiration for the patterns was based on "Brain corals"
"Brain corals" have a complex folded surface, that visually creates a pattern often resembling a brain. However, they all have their own unique shapes and patterns (image b).

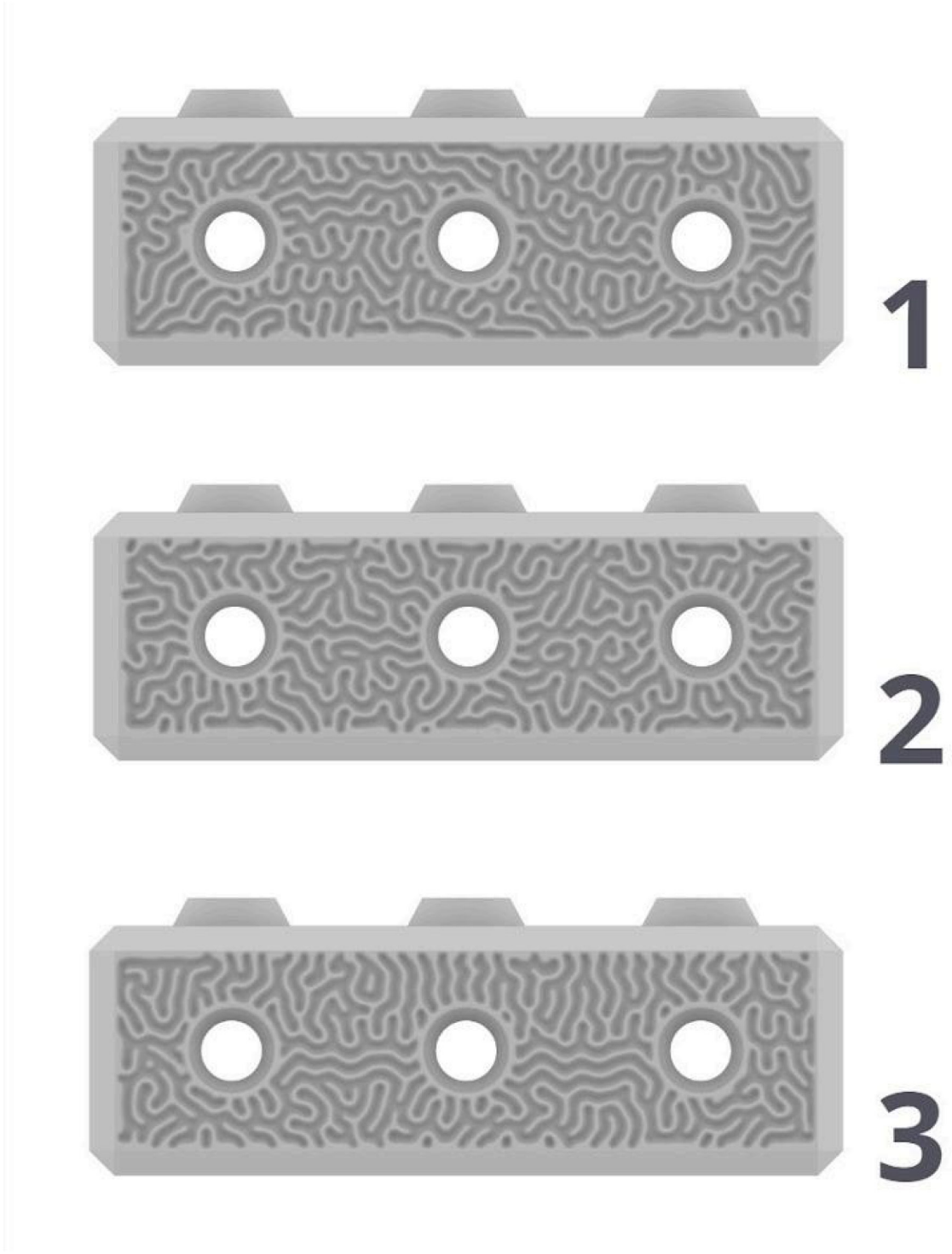
Image b: Different types of Brain corals



Evaluating the proposed patterns

In this next section I want to ask you to select which of the 3 proposed designs fits each statement best. Try to answer the 6 statements quickly and with your first instinct.

The proposed patterns: 1, 2 & 3



1. This pattern is visually most attractive to me: *

- ○ 1
- ○ 2
- ○ 3

2. This pattern reminds me of a Brain coral the most: *

- ○ 1
- ○ 2
- ○ 3

3. This pattern visually looks like it was designed specifically for the ReefBlocks the most: *

- ○ 1
- ○ 2
- ○ 3

4. This pattern has the most balanced design: *

- ○ 1
- ○ 2
- ○ 3

5. This pattern I think best fits in a marine context: *

- 1
- 2
- 3

6. This pattern helps 'break' the rectangular shape of the ReefBlock the best: *

- 1
- 2
- 3

Thank you for participating in this survey!
If you have any additional comments you would like to share with me, feel free to leave them here:

Jouw antwoord

Verzenden

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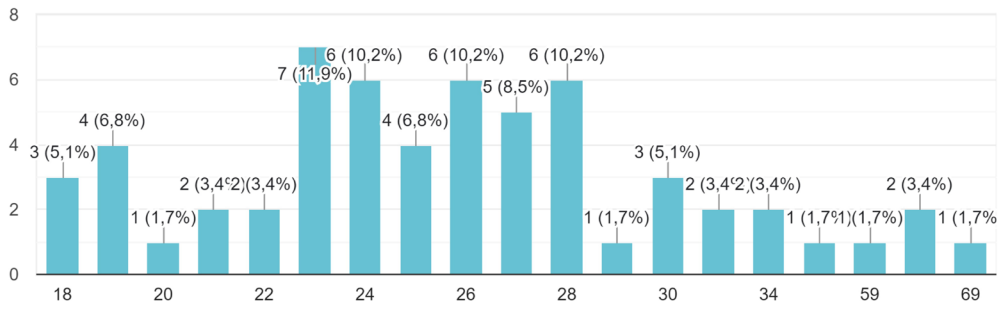
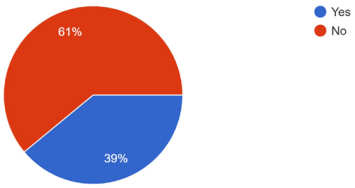
1.D.1 | Aesthetics survey results

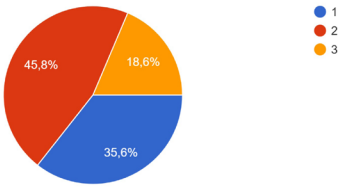
My age is:
59 antwoorden



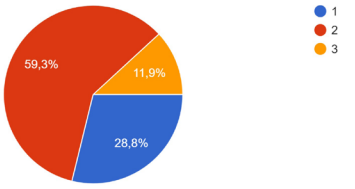
I have seen a natural reef in real life under water:
59 antwoorden



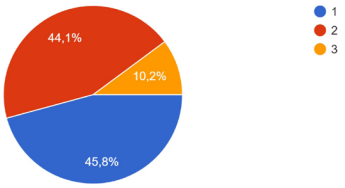
5. This pattern I think best fits in a marine context:
59 antwoorden



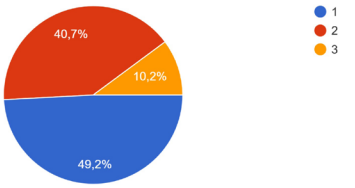
1. This pattern is visually most attractive to me:
59 antwoorden

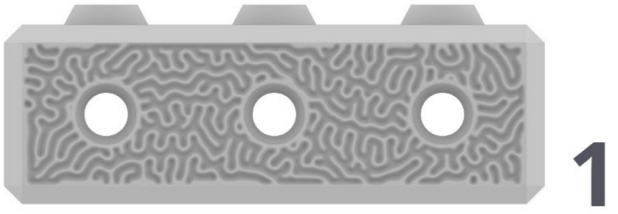


6. This pattern helps 'break' the rectangular shape of the ReefBlock the best:
59 antwoorden

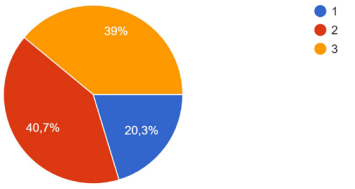


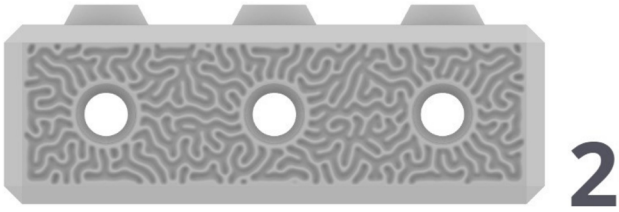
2. This pattern reminds me of a Brain coral the most:
59 antwoorden



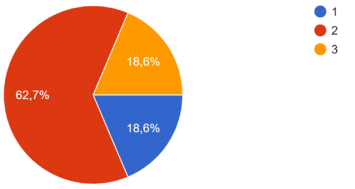


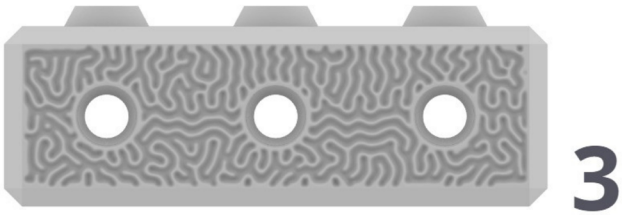
3. This pattern visually looks like it was designed specifically for the ReefBlocks the most:
59 antwoorden





4. This pattern has the most balanced design:
59 antwoorden





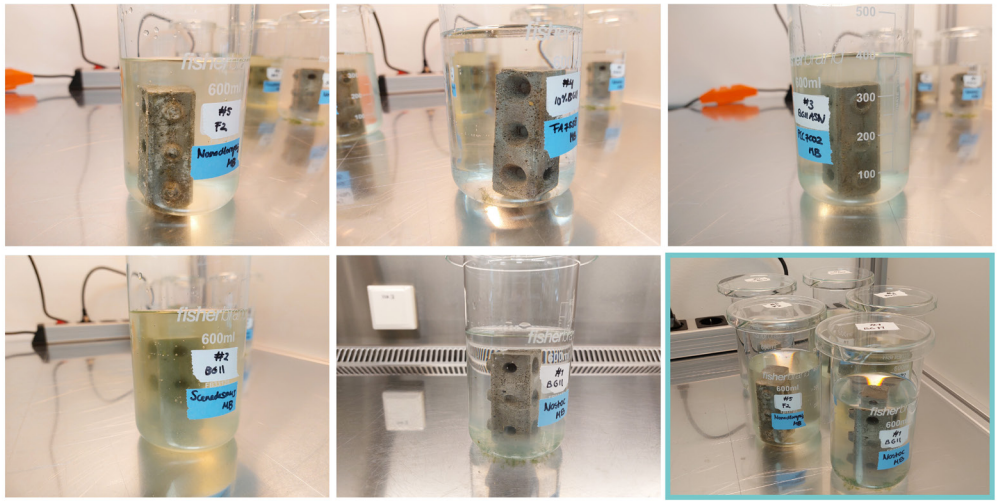
E | Preliminary microalgae tests

1.E.1 | Microalgae test 1

Preparation



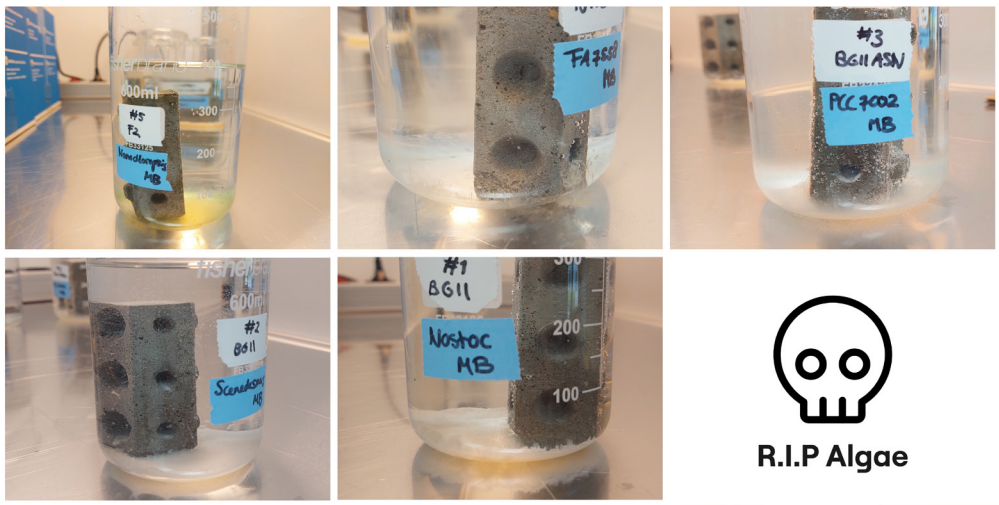
Day 0: submerging 5 strains of different algae with small ReefBlock prototypes



Cloud formation between the concrete and BG11 mixes started almost immediately

But it was decided to proceed with the small-scale test

Day 2: Almost all algae died due to a reaction between the concrete and the medium



R.I.P Algae

Within one or two days the algae were all dead

Nanochloropsis in F/2 medium survived the longest

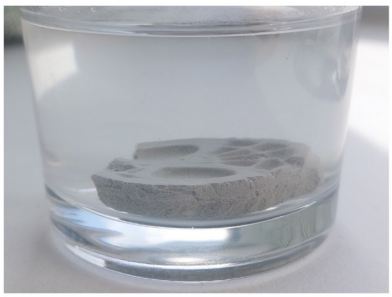
Next steps
Try submerging the concrete in demi-water for at least 2 or more days

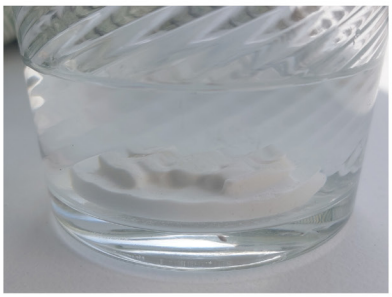
Next steps
Try different material compositions with the medium to see if a reaction occurs again

1.E.2 | Material test

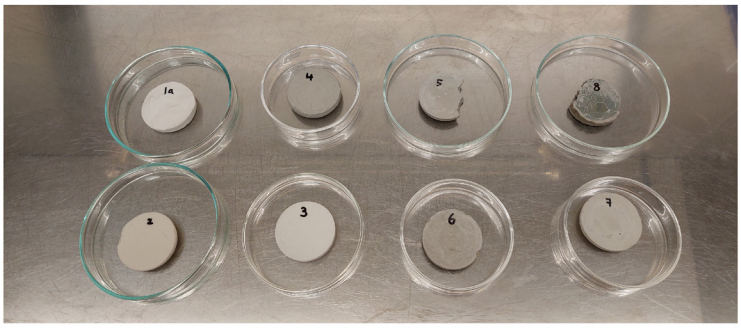
Preparation







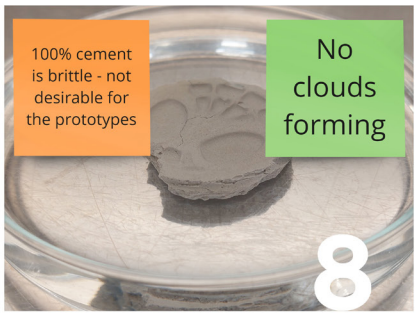
Test setup



1a: 100% gypsum
2: 100% gypsum, leached in water for 2 days
3: 100% PLA (3D printed)
4: PLA print with a layer of 100% cement
5: 100% cement
6: 50% cement 50% sand
7: 50% cement 50% gypsum
8: 100% cement, leached in water for 2 days

Most relevant results





Conclusion
Leached cement shows great potential but for structural integrity try the concrete mix with sand





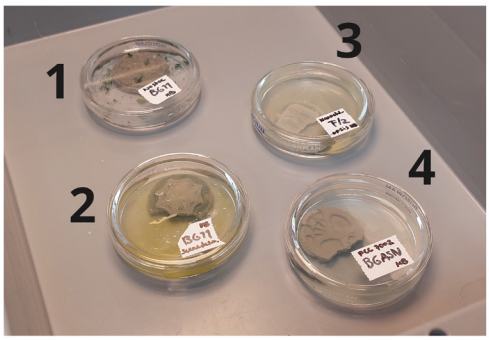
Next steps
Leach the prototypes for a week longer and start algae test 2 to see which algae strains are now able to survive

1.E.3 | Microalgae test 2

Preparation



Test setup



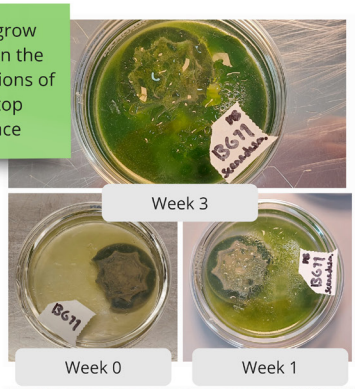
All prototypes leached in demi-water for 5 days and refreshed once

Limitation:
To spare time, I reused 3 different sample types from the material test, which means that these samples are not fully comparable. Especially, the Nanochloropsis seems to have died, even though last time they survived the longest. This is very likely due to the gypsum in the mix with cement. Gypsym dissolves over time, and may have caused a disbalance of minerals in the medium, which clearly the algae could not handle.

1: *Nostoc* sp.
2: *Scenedesmus* sp.
3: *Nanocholoropsis* sp.
4: *Synechococcus* sp. (PCC 7002)

Results

They grow most on the depressions of the top surface

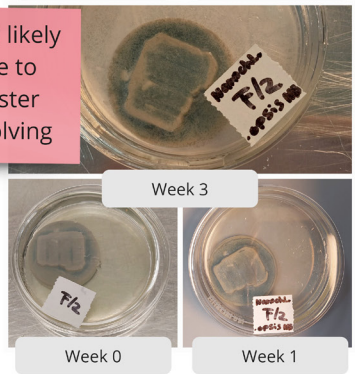


But then they revived and they grow most on the smoother surfaces

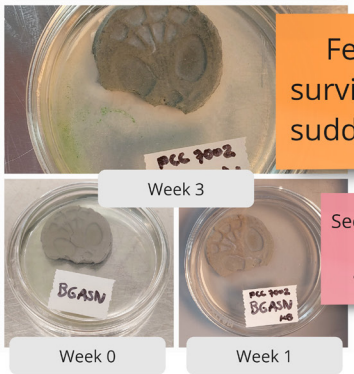


They seemed to be dying

Dead likely due to plaster dissolving



Few survivors suddenly

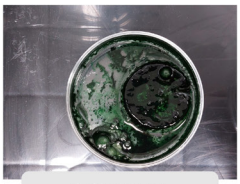


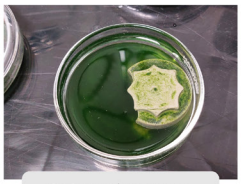
Seemingly dead algae

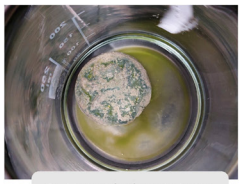
Conclusion
Nostoc sp. and *Scendesmus* sp. showed greatest potential with regard to survival, visibility and growth rate

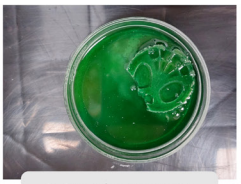
Next step
Later the Nanochloropsis was also tried with cement instead of a plaster mix, to see if it is the material or that the algae do not survive being submerged with a prototype either way

Bonus results after a few months


1: *Nostoc* sp.


2: *Scenedesmus* sp.


3: *Nanocholoropsis* sp.

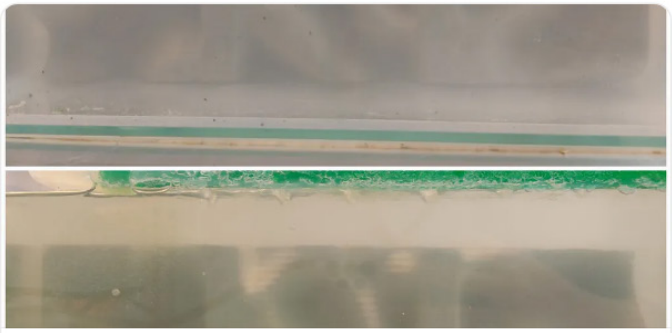

4: *Synechococcus* sp.

F | Microalgae test documentatino remarks per week



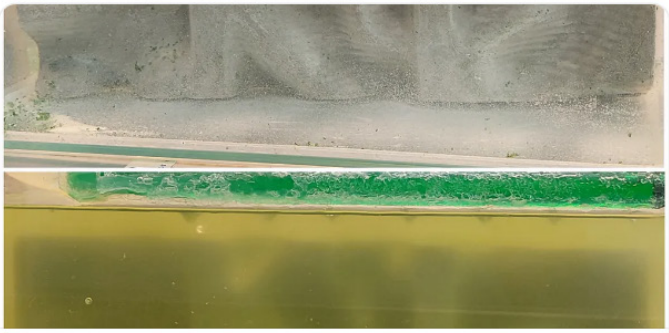
Day 0 (03/09/2024)

Visible development:
Nostoc clearly shows the circulation of the water in a wave-like pattern as they are individual flocks of algae. Whereas Scenedesmus is diluted in the medium. Already some lee areas on the surface topography visibly 'recruiting' Nostoc flocks.
Additional remarks:
After autoclaving the concrete prototypes had a thin dust-like layer; however to keep them sterile, I did not clean the dust off.



Day 1 (04/09/2024)

Visible development:
Nostoc is visibly still in the same lee areas in the surface topography, as well as on the top. And Scenedesmus seems to be mainly settling on the top of the prototypes and slightly on the sides. In both tanks clear lee areas behind the pump are visible, as the largest colonies are present there, and unfortunately not being picked up by the pumps.
Additional remarks:
Some clouding did occur in both the aquariums, likely due to the 'dusty' layer on the concrete. Some 'dust' is also visible on the bottom of the tank and on top of the prototypes. I am anxious to see if this will not be the downfall of the algae. In order to distribute the algae better, I turned up the pomp speed slightly, but not too much to prevent knocking the algae off again.



Day 7 (10/09/2024)

Visible development:
Cloudiness seems to have cleared, but still large accumulation of especially Nostoc algae behind the pump. However, clear favorable zones are starting to take shape with the Nostoc. Unfortunately, the visibility of the concrete prototype in the tank with Scenedesmus is blocked by the greening of the medium, which makes it hard to identify the favorable areas of this algae. It does however suggest a good increase in algae growth.
Additional remarks:
Still, in both tanks dust is present and it is uncertain what are dead algae and what is dust. In order to help the growth of Nostoc algae on the prototypes along, we used a pipette to suck up the accumulated algae and dispose them in front of the prototype again. This helped the spreading of the algae at least for a while.



Day 14 (17/09/2024)

Visible development:
Very clear development of both algae types on the surfaces. Even more interestingly, they show exact opposite behavior with where they attach. Nostoc clearly preferring the lightest, most exposed areas, and Scenedesmus clearly preferring the more sheltered areas, avoiding to be exposed.
Additional remarks:
No changes are needed to the test setup, curious how they will further develop, but this already gives a very clear preference and different behaviors.



Day 21 (24/09/2024)

Visible development:
Nostoc is clearly expanding from where it was attached, with most concentration on control panel 2 and sample C. Clearly they rather attach to the top side of a horizontal crevices, than on vertical crevices; which is opposite to my hypothesis. Scenedesmus does not seem to be expanded much since last week; still mainly in the depressions of the ridges

Additional remarks:
Film formation on the bottom of the Nostoc tank had partially come loose but still attached near the front of the tank, so I made sure that it was cut loose to improve visibility and spread more algae throughout the tank. Both Nostoc and Scenedesmus are starting to attach to the side walls of their tanks, making visibility worse by the day.



Day 28 (01/10/2024)

Visible development:
It is becoming hard to see, but the algae growth seems to continue very well. The Scenedesmus is starting to become more planktonic again and greening the water like on day 7. Nostoc is starting to grow one big film formation over the bottom of the tank and the front glass, making it harder to take picture.

Additional remarks:
Due to the overgrowing in the tanks, I can no longer take clear pictures from the front because of a glare.