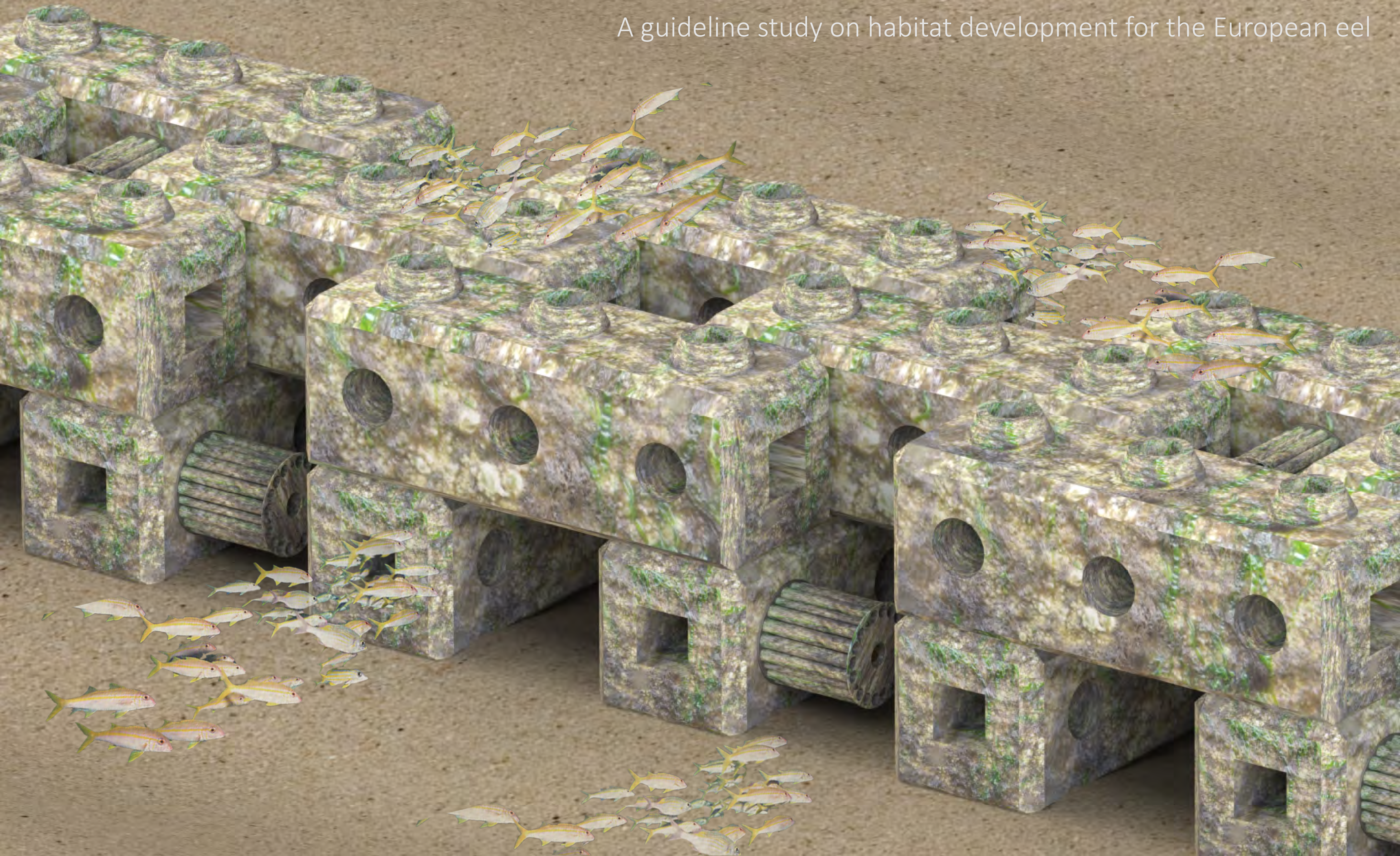
Design of a bioreceptive ecological enhancement for a marine infrastructure

A guideline study on habitat development for the European eel



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Summary

This thesis describes the development of an innovative product, The EcoModule. The innovation enhances a marine infrastructure called, Reef Enhancing Breakwater (REB) developed by the startup Reefy. This breakwater prevents coastal erosion and it provides a habitat substrate for marine organisms, with the aim of boosting biodiversity. The Reefblocks used for this purpose provide habitat to micro-organisms, however, macro-organisms are also needed to keep an ecosystem running. Therefore, the EcoModule focuses on attracting and providing habitat to macro-organisms.

The habitat described is this document was developed for the endangered European Eel. This document offers a concise step-by-step design process on how to design a habitat for a specific marine organism. In the future, when a different organism is targeted, this thesis can be used as a guideline, with the EcoModule functioning as a basis because of its user-friendly customisability.

First, an introduction of the context is described followed by a case study on the European Eel. The aspects for habitat development that need to be taken into account are described, after which the final design is presented. The structure of the product is visualised, clearly showing which parts are designed for what and why.

It has been proven that the EcoModule can be attached to the REB and does not adversely affect its operation. A test in a relevant environment has been conducted to investigate the behaviour of the European Eel across different materials and habitat dimensions.

All this has resulted in an innovative proof of concept that will be the first step towards building ecosystems and boosting biodiversity.

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1. Introduction

1.1 Project context

Climate change brings negative consequences. Sea level rise has turned coastal erosion (Figure 1) into a significant issue [1] (Vitousek et al., 2017) and coral reefs are disappearing due to the warming of sea water [2] (Hinrichsen, 1997). Coral reef covers only 0.01% of the seabed, however, it supports 25% of marine life (Wood, n.d.) and 97% for dissipating wave energy before it reaches the shoreline (Ferrario et al., 2014).

Reefy addresses the above mentioned issues by combining coastal engineering and marine biology to create a nature-inclusive marine infrastructure. Reefy has successfully developed the first modular artificial reef capable of dispersing wave energy to safeguard the coast while simultaneously offering the necessary foundation and habitat structures to enhance marine biodiversity. This patented coastal infrastructure is called Reef Enhancing Breakwater (REB).

This is achieved through the implementation of Reefblocks (Figure 2). These, each weighing 6.3 tonnes, concrete blocks measure 3x1x1 meter and use an inner tubular system to dissipate wave energy and offer habitat structures (Figure 3).

Figure 1: Coastal erosion

Figure 2: Reefblock

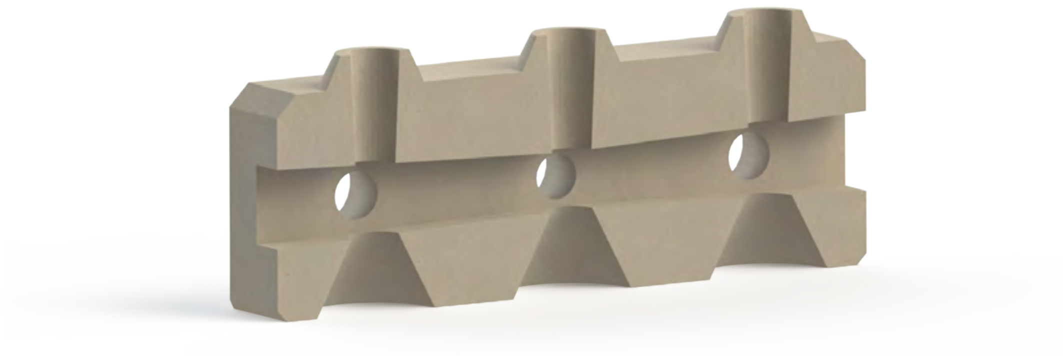

Figure 3: Inner tubular system

The Reefblocks are stacked in a configuration (REB) on the reef; a narrow ridge or chain of rocks, shingle or sand, lying at or near the surface of the water (Cumings, 1932) and are designed to fit together and remain stable without fasteners (Figure 4).

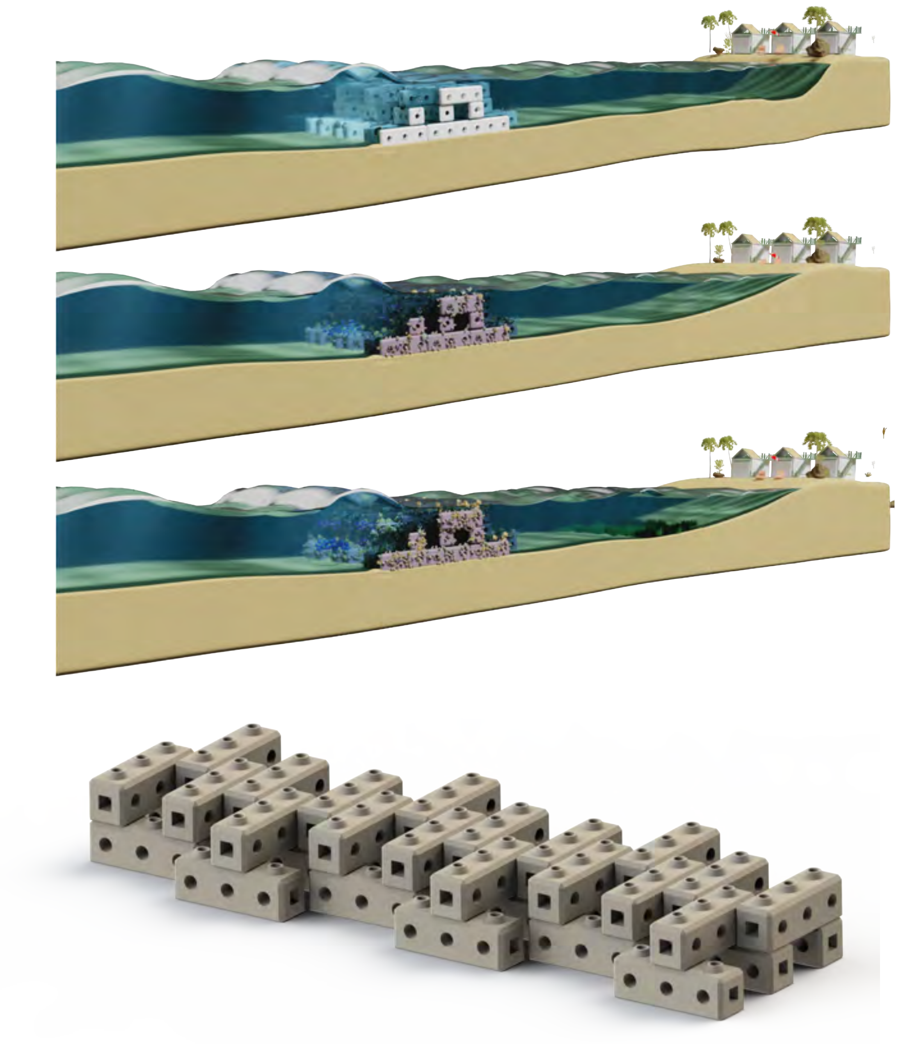

Figure 4: Reef Enhancing Breakwater

The REB has **two** functions:
[1] Primary function: Coastal protection
[2] Secondary function: Provide habitat structures to enhance marine biodiversity.

This thesis focuses on the <u>secondary function</u> of the REB.

Improving the secondary function will improve the primary function, because improved biodiversity will change the REB structure in shape and expand in volume. This modification will improve dissipation of wave energy. (Ferrario et al., 2014).
To improve biodiversity, an ecosystem will have to emerge around the REB. For an ecosystem to succeed, four trophic levels (Figure 5) of organisms are needed: Producers, consumers, grazers and predators (Little et al., 1996).

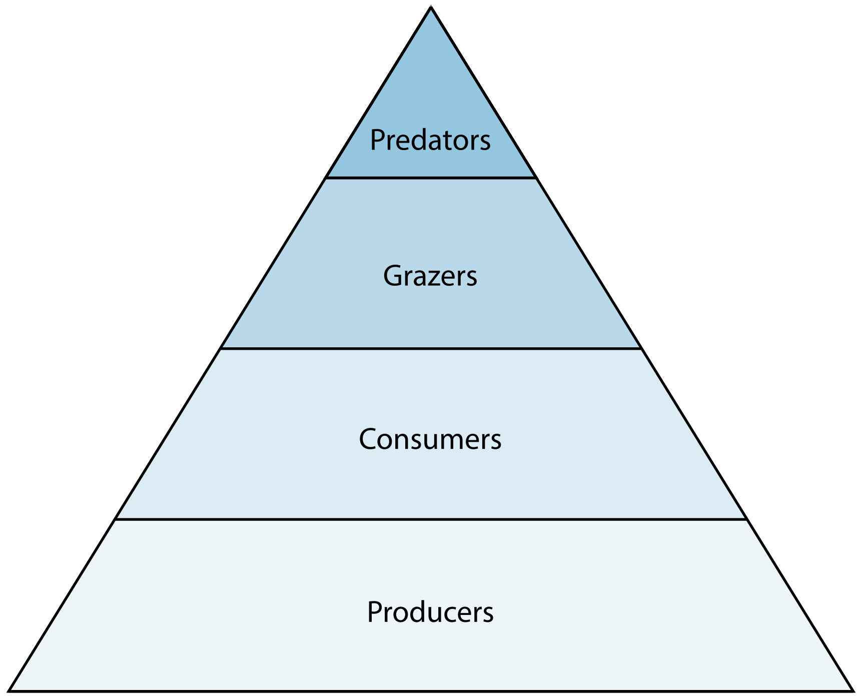

Figure 5: Trophic levels

Reefy focuses on two ways to provide habitat:

1. The use of bioreceptive materials

Bioreceptivity is the aptitude of a material (or any other inanimate object) to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration (Stohl, 2023). The start-up has succeeded in growing coral on both biodegradable biopolymers and low-emission cement-free geopolymer concrete. Reefy has also succeeded in allowing micro-organisms to colonise the Reefblocks (results from pilot: Rotterdam Reef, Figure 6).

The start-up is innovating in this area with surface finishes/additions such as Reef-paint and textures. Both the use of bioreceptive materials and these innovations focus on increasing the ability of the Reefblocks to be colonised by micro-organisms (producer and consumer) needed to initiate an ecosystem (Reynolds, 2016).

2. An inner tubular system

The inner tubular system was designed to dissipate wave energy and prevent the Reefblocks from tilting or lifting. The internal system could act as resting, hiding and reproduction places, however, the system offers limited space and is not purposefully designed to fulfill this function. This results is low utilisation by macro-organisms (grazers and predators). These organisms are not attracted by bioreceptive materials but by habitat areas and micro-organisms that colonise these materials (Little et al., 1996).

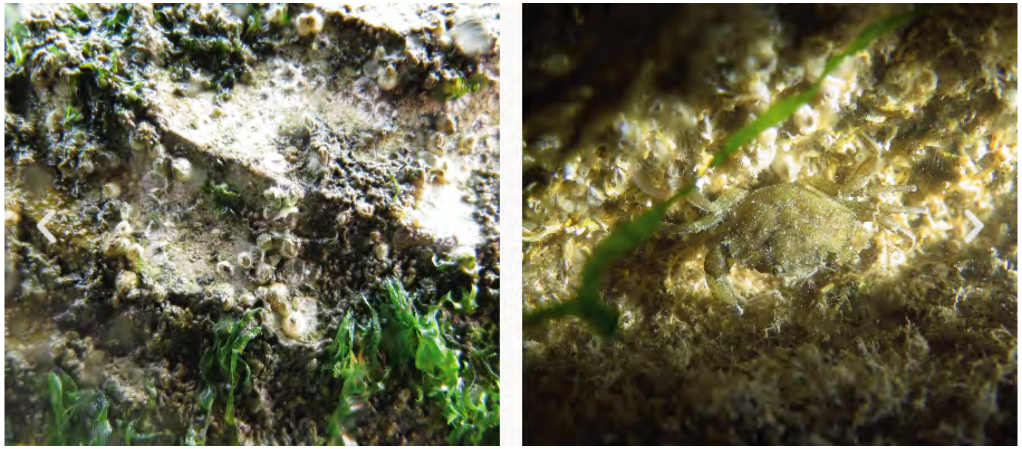

Figure 6: Colonisation on Reefblocks

1.2 Problem definition

The bioreceptive concrete and inner tubular system of the Reefblock provide habitat and the ability to be colonised by marine organisms. However, as discussed in the project context, the Reefblock was designed for the primary function. At present, Reefy has succeeded in fulfilling the primary function and part of the secondary function, namely organisms (producers and consumers), colonising the Reefblocks.

The problem is providing habitat for macro-organism (grazers and predators). The inner tubular system should fulfill this function, however, this internal structure offers limited resting, hiding and reproduction places and is not designed to the needs of specific organisms.

An initial concept, the Ecoblock, should provide a solution for this (Figure 7). The Ecoblock is an add-on to the REB that should attract local grazer and predator organisms, which are not comfortable with living in the inner tubular system. What this block will look like geometrically, how it will attract organisms and how it will be attached has not yet been examined.

A Minimal Viable Product (Figure 8) has been tested, this product broke down because it could not withstand wave energy and therefore did not generate any results

The EcoBlock has been the drive for the assignment from Reefy: Design of Cubic Ecological Enhancement for Marine Infrastructure (Full assignment, Appendix 1). This block must undergo a revision process based on sustainability, durability, feasibility and viability.

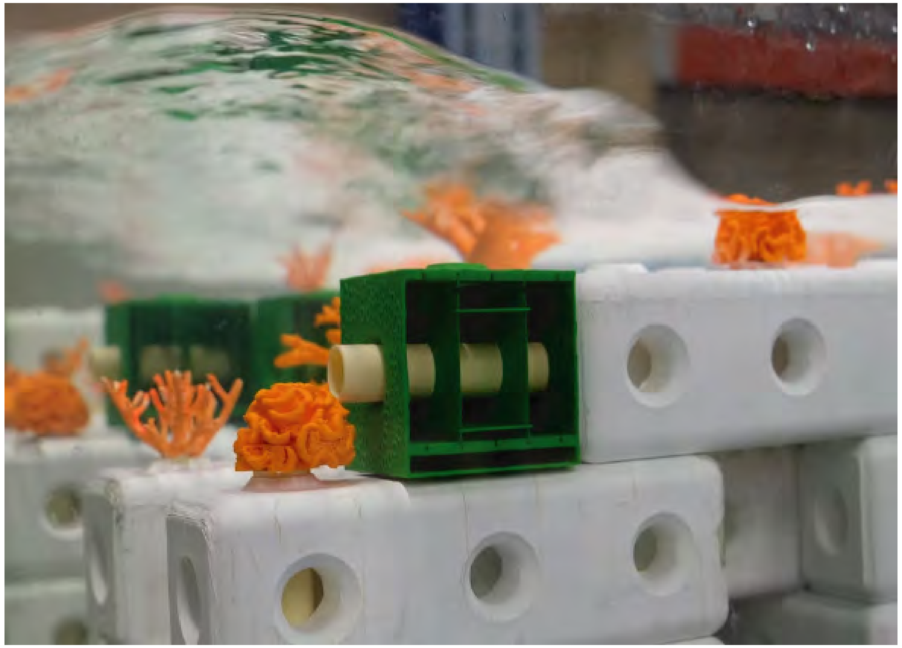

Figure 7: The Ecoblock

Figure 8: Minimal viable product

1.3 Vision

The primary function of the product (Figure 9) is to facilitate habitat for grazer and predator organisms that are not comfortable with living in the inner tubular system of the Reefblocks. Thereby, as a secondary function, the habitat is made of a bioreceptive material to provide the opportunity to be colonised by micro-organisms (producers and consumers). Colonisation of the product gives the habitat a natural appearance, which is beneficial for attracting grazers and predators (Little et al., 1996).

In this thesis, in consultation with Reefy, the European Eel was chosen as the end user. This choice arose from two reasons:

1. The European Eel is listed in the Convention on International Trade in Endangered Species (Barcala et al., 2022). The cause of this, besides fishing mortality and natural mortality, is habitat loss (Bevacqua, 2015).

2. The eel is also called the omnivore, this predator eats consumers, grazers as well as other predators and is therefore well suited as a participant in an ecosystem.

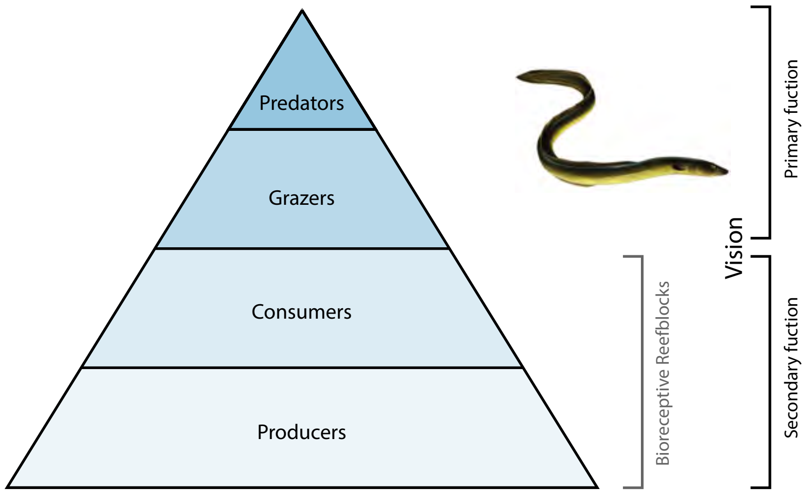

Figure 9: Primary and secondary function

How marine ecosystems work is described in Chapter 5.1.1: Marine ecosystems.

This thesis demonstrates a first study on how to design a product for a specific marine grazer or predator organism. In this case for the European Eel. This does not mean that Reefy will sell the product as 'Eel habitat' but as initial evidence on the potential of habitat development and thereby boosting biodiversity. This project takes this a step further by developing a product that is easy to adapt to the needs of another species. Should a future study be done on another grazer or predator organism, this thesis can be used as a guideline and the product as a basis.

The Ecoblock and the assignment set up by Reefy have been used as the basis in this thesis. The assignment has been rewritten and is visible in the Project brief (Appendix 2). This brief and research led to the following vision:

Design of a customisable bioreceptive habitat that complements the Reef Enhancing Breakwater, tailored to meet the needs of specific grazer/predator organisms, and thereby enhancing biodiversity in marine ecosystems.

To be able to use the product as a basis in the future, **customisability** is one of the main requirements (Appendix X). One (simplistic) housing will be developed that allows for different configurations. The configuration can be **tailored** to the needs of marine species living in a specific area. The product **complements** the existing REB instead of modifying the Reefblocks. The product uses **bioreceptive** materials which offers the possibility of being colonised and thus gives a natural appearance which is conducive to the attraction of grazer and predator organisms.

1.4 Scope

In this twenty-week project, the focus lies on two main topics.
The development of a customizable module [1] and analysing the behaviour and habitat of the European Eel [2]. Combination of both will lead to the EcoModule.

Customisable module [1]
One standard housing, a fastening method (structural parts) and customisable parts (non-structural parts) are developed that form the basis of the module. Each part is accompanied by a manufacturing strategy and assembly of the product is shown.

Eel behaviour and habitat [2]
Since the eel is non-human, designing for this user is a challenge. Literature, experts and real-time testing are used to investigate the behaviour of the eel. This research will be used in the development of the module.

Whether the Eel (and other marine organisms) will live in and around the module for an extended period of time and whether biodiversity is improved in and around the REB, is beyond the scope of this project. However, it is possible to test and validate the influence of the product on the REB at scale and the behaviour of the Eel around a 1:1 prototype. The final design will therefore be a proof of concept for the Eel with a substantiated discussion and recommendations for further development.

Product development goes up to Technology Readiness Level 5: Validation of prototype in relevant environment. The timeframe for production of the final product is 2025. This means that the product should be producible using current technologies.

1.5 Approach

The goal is to deliver a product that includes a manufacturing strategy for creating a habitat which enhances biodiversity around the REB by attracting specific local marine organisms (in this thesis: the European Eel)

This goal will be developed in a 20-week time frame. This thesis represents a design process from the orientation phase to a proof of concept. The schedule of this project is shown in Appendix 3.

The schedule is translated to the Double Diamond design method. This is a design process divided into four phases: Discover, Define, Develop and Deliver. Figure 9 shows how the phases are classified. Within this design process, desirability, feasibility, viability and sustainability will be taken into account.

The strength of this method lies in the divergence and convergence within the design process. This technique will ensure that tunnel vision is not created and creativity is stimulated. The method seems very straight forward, however, this method does not exclude iteration steps, which can be taken in a specific design phase as well as throughout the process. This method also helps in setting deadlines, forcing you to make choices that contribute to completing the project within the time scope.

Discover
Research was done on the European Eel, how marine ecosystems around reefs work, competitors, stakeholders, the Ecoblock and suitable materials. This phase of the process was done to broaden knowledge, understand the context and diverge in the design process to generate different ideas using these discoveries.

Define
A combination of generated ideas are defined into one concept. Requirements and discussion/brainstorm sessions with fellow students, experts and Reefy assisted in the concept choice that will be further developed in the next phase.

Develop
The chosen concept is further developed and detailed. Several 1:20 prototypes and a 1:1 prototype are developed to get acquainted with different material properties and to meet challenges that may arise when developing the final concept. These prototypes will be tested in the deliver phase.

Deliver
The 1:20 scale prototypes are tested on the influence of the product on the REB, to determine the placement. The 1:1 prototype has been deployed to investigate the behaviour of the eel towards habitat- material and dimensions. These tests helped finalise the proof of concept.

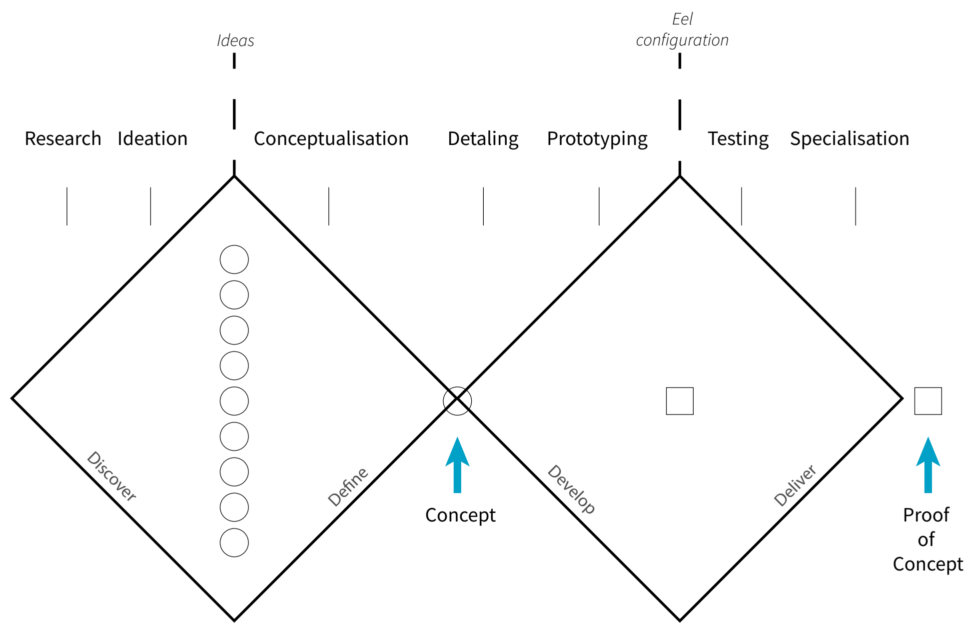

Figure 9: Double Diamond method

2. The European Eel

The European Eel (Figure 10), is listed in the Convention on International Trade in Endangered Species (Barcala et al., 2022). Due to the complex lifecycle of the eel, which reproduces in open sea water and spends the longest time of its life in continental waters, this species encounters a huge geographic range and a variety of habitat. Accoording to Bevacqua (2015), habitat loss, fishing mortality and natural mortality play a major role in eel decline. To contribute to the recovery of the Eel, habitat is provided using the EcoModule.

To gain knowledge about the Eel, an expert was approached, he conducted research on the behaviour and habitat of the Eel. The expert facilitated a paper (Klein Breteler, 2005) which was used, among other sources, in the design of the EcoModule.

Figure 10: The European Eel

2.1 Lifecycle

The European Eel reproduces and lays its eggs in the Sargasso Sea, a sea in the Atlantic Ocean off the coast of North America. From these eggs, pre-leptocephalus larvae (Length: 0.5-0.7cm) are born and start their journey towards Europe in search of fresh water. During this journey, the leptocephalus turns into a glass eel (Length: 5.4-9.2cm). The glass eels arrive at the continental waters of Europe. In these waters, the eels grow into Red Eels (6.9-133cm) (Figure 11).

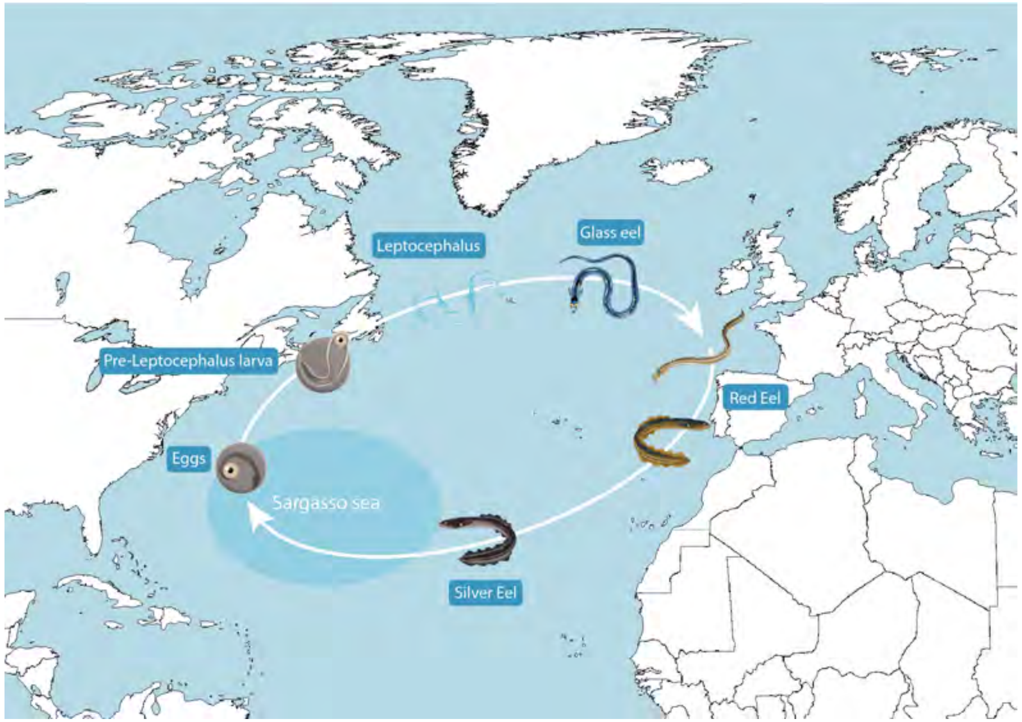

Figure 11: Lifecycle

In many cases, the eels have to pass through a dike or sluice to enter freshwater. This makes it difficult for the eel, although more and more eel-friendly sluices (figure 12) and ditches are being built (Figure 13).


Figure 12: Eel sluice


Figure 13: Eel ditch

The eel spends most of its life in the fresh/saline/brackish continental waters of Europe. When fully grown and thus sexually mature, the Red Eel is called the Silver Eel (Length: 21.2-44.4cm (m) and 26.4-101cm (f)). The Silver Eel begins its journey back to the Sargasso Sea to reproduce and lay eggs.

The fact that Eels reproduce and lay eggs in salt water has been proven, however, it has not been proven why this species chooses the Sargasso Sea (Klein Breteler, 2005).

Glass, Red and Silver eels are found in fresh, brackish and salt water. The EcoModule is placed in salt water, providing habitat for each of the above eel species.

2.2 Habitat

The eel is a predator that is active towards the end of the day and at night. When not migrating, the eel hides in cavities, among plants, stones, rocks, stumps and wreckage. The eel shelters itself from daylight and predators (Figure 14).

An interesting phenomenon of the eel is wriggling/entrenching itself in soft, sandy, muddy grounds. The Eel wriggles, like ' corkscrew' with its tail first, into the bottomground. Its eyes are just above the surface (Figure 15), the eel can see its prey and launch an attack (Klein Breteler, 2005).


Figure 14: Shelter


Figure 15: Ground habitat

As mentioned in the previous sub-chapter: Lifecycle, eel chutes/pipes are made next to locks and dykes to provide a passage for eels. Willow branches (Figure 16) and coir rope (Figure 17) are used as fill material. The eel is attracted to this material and can cling to it which makes movement easier (Klein Breteler, 2005).


Figure 16: Willow branches


Figure 17: Coir rope

Not only do eels hide in or under natural materials, but also in or under objects that have entered the water. Accoording to Kleine Breteler (1999), eels hide in tubes/pipes. Multiple eels hide in the same tube if space permits (Figure 18).

Figure 18: Tubes/pipes as eel habitat

The eel's behaviour regarding habitat types and materials is included in the final design of the EcoModule. To investigate which material and size of habitat is preferred, a 1:1 scale prototype was developed and tested in a recreational fishing pond at WILD 'bijzonder vissen' where eels are present. The results of this study are presented in Chapter 5.4.2: WILD bijzonder vissen. The abovementioned study was confirmed by an employee of WILD bijzonder vissen. The ground surface of the eel pond they own is full of pvc tubes to provide habitat for the species. It was also told that sometimes an eel is caught together with a pvc tube because the eel grabs onto it.

2.3 Food

The eel is part of the Mobile vertebrate predators category, which prey on consumers and grazers (Little et al., 1996). The species eats invertebrates, fish, crustaceans (razor clams, Figure 19), molluscs (triangular mussel, Figure 20), annelids (worms, Figure 21), insects, larvae and eggs.

Figure 19: Crustaceans; Razor clams

Figure 20: Molluscs; Triangular mussels

Figure 21: Annelids; worms

To attract the eel, a bioreactive material colonised by crustaceans, mollusks and annelids will have to be used. According to Brown (2005), the materials PVC, Concrete, steel and wood are suitable for these organisms. Chapter 5.1.4: Materials, describes a study on different suitable materials for artificial reefs and the EcoModule.

3. Guideline on habitat development

This chapter describes concise steps on how to develop a marine habitat for a specific organism. These steps can be used as guideline when researching an alternative organism.

Guideline

1. Orientation in context
- -Market analysis
- -SWOT analysis
- -Stakeholder analysis

2. Research on marine ecosystems, artificial reefs and suitable (bioreceptive and wave energy resistant) materials

3. Engage external parties and make them stakeholders, to gain knowledge and get acces to testing facilities

The orientation and research phase helps to draw a list of requirements (Appendix 5), on the basis of this list, the design process will start. During the process, challenges (Appendix 6) will occur and the requirements will be supplemented and adapted. Furthermore, sustainability, feasibility, desirability and viability must be taken into account during the process to develop:

***A:** A structural, wave-energy resistant housing*

***B:** Non structural customisation parts designed to make a marine habitat attractive. Focus on four main aspects:*
- -Geometry
- -Natural appearance
- -Food
- -Fill material

When designing a new product, both A and B must be taken into account. When adapting the EcoModule to the needs of another organism, only B must be considered.

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Example: The EcoModule

1. Habitat space should be expanded, the design should be simple, cheap, have a low CO2 emission and be easy to install. With an ecological enhancement, Reefy will be the first on the market, giving it a strong competitive position. (See Appendix 4 for full analysis)

2. The EcoModule uses three materials ideal for attracting organisms with steel serving as structural housing, PVC tubes for enclosure and habitat (preferred by the eel) and wood as colonisation surface and partitions for internal habitat areas.

3. WILD 'bijzonder vissen' and Deltares have been approached. The organisations provided test facilities that helped with the design. WILD for eel behaviour and habitat, Deltares for testing the influence of the EcoModule on the stability of the REB

A: Housing of the EcoModule: Round shape (low resistance), low carbon steel (high strength and durability), strong fastening method, easy to install.

B: Customisation parts

Geometry

The geometry a habitat has, determines the organism that will use it. This was investigated through research on eel behaviour and testing a 1:1 prototype in a relevant environment (TRL 5). Results: 80x600mm PVC tubes and internal habitat area's devided by wooden panel. (Chapter 5.4.2: WILD bijzonder vissen)

Natural appearance

A natural appearance of the habitat can be achieved by using bioreceptive materials that will be colonised by marine organisms. (Chapter 5.1.4: Materials)

Food

The presence of food in or on the habitat attracts predators. In an ecosystem, organisms eat each other. Therefore, research was conducted on how marine ecosystems (Chapter 5.1.1) work and which materials (Chapter 5.1.4) are colonised by producer, consumer and grazer organisms in order to facilitate specific food for the European eel.

Fill material

Research was done on materials that eels hide in or under. Several materials were tested with a 1:1 prototype in a relevant environment (TRL 5). Result coir rope/fibre (Chapter 5.4.2: WILD bijzonder vissen)

4. The EcoModule

The EcoModule (Figure 21) is an ecological enhancement for the marine infrastructure called Reef Enhancing Breakwater. This add-on module provides habitat for the European Eel and provides adaptability when a different pradator or grazer organism is explored. In this chapter, the EcoModule is presented as a configuration for the eel.

Grazer and predator organisms are needed to keep an ecosystem running. Not only does this module provide resting, hiding and reproduction places for these organisms, but, through the use of bioreceptive materials, it will also allow for colonisation of micro-organisms (producers and consumers). This will give the EcoModule, over time, a natural appearance and provide food, which is beneficial for the attraction of grazer and predator organisms (Little et al., 1996).

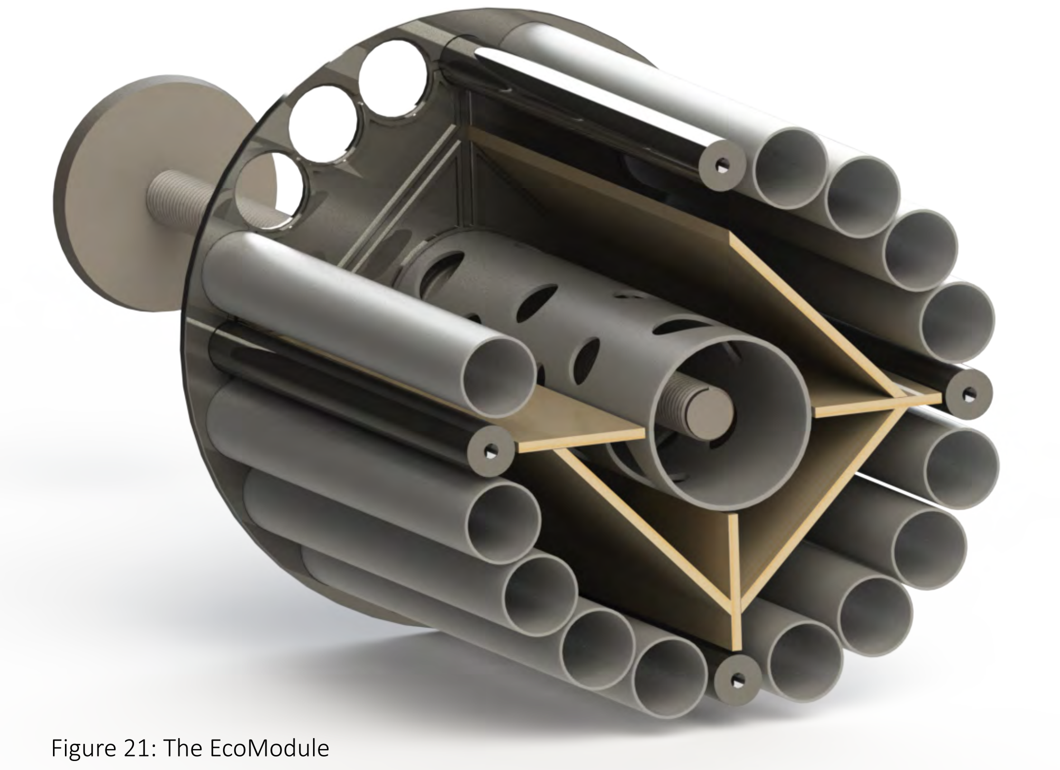


Figure 21: The EcoModule

The EcoModule has a diameter of 600mm and a length of 600mm (the average length of the largest Eels; Red and Silver eel, Chapter 2). These dimensions allow the EcoModule to fit any location in the REB. The length is scalable up to 800mm and can be made as short as desired (Chapter 4.5: Placement).

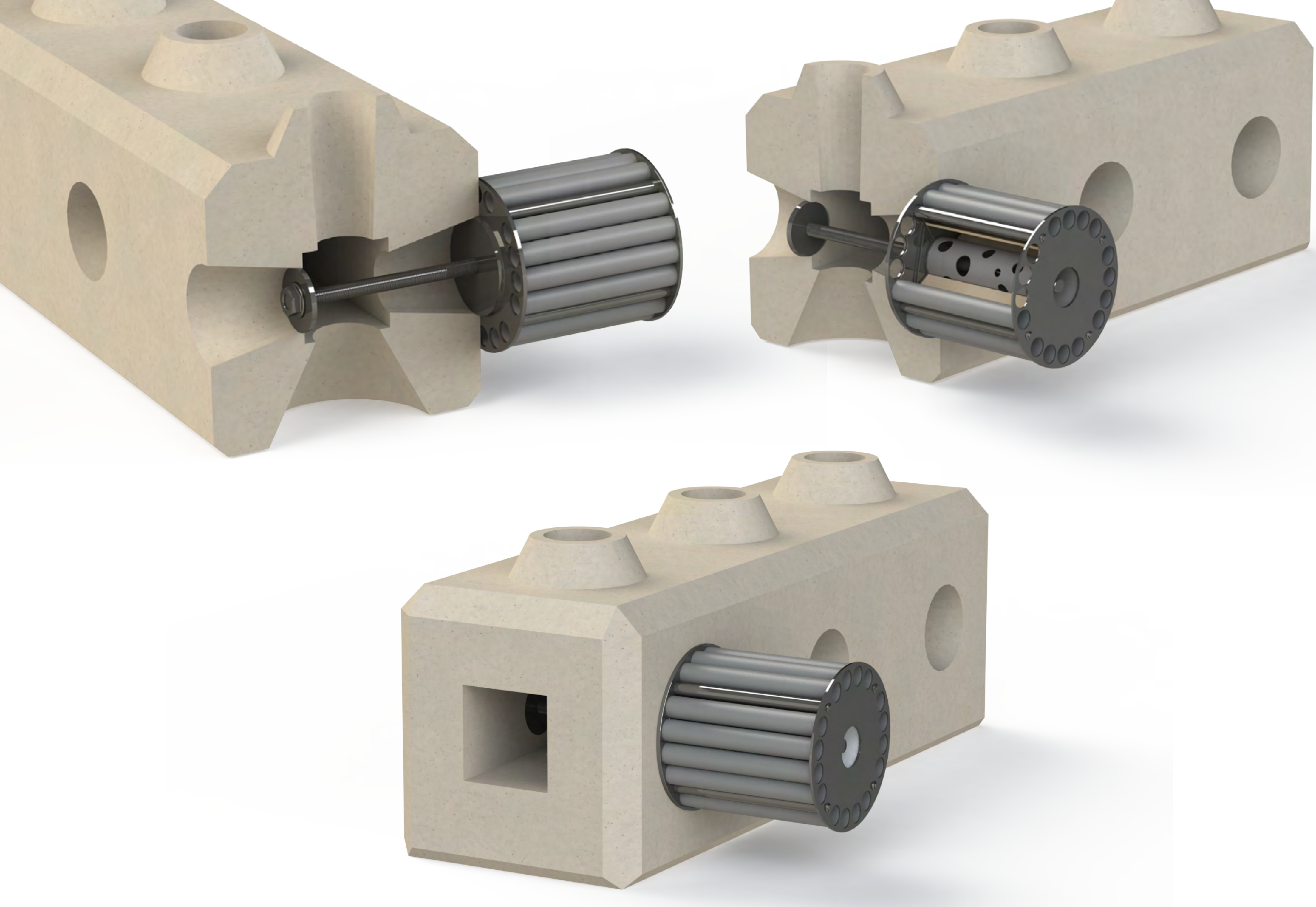
Accoording to research (Chapter 5.1.4: materials), three materials are used: Recycled Q235 carbon steel (strong, suitable for construction and engineering structures, low cost, durable: Emma, 2021 and bioreceptive: Zhang et al., 2008; Southwell et al., 1974) as structural parts, polyvinylchloride (low cost, high durability; Folkman, 2014, low micro plastic degradation; Mintenig et al., 2019, desired by eels Klein Breteler, 2005; Results TRL 5 test: Chapter 5.4.2: WILD bijzonder vissen, bioreceptive: Brown, 2005) and Populus wood (low cost, lack of toxicity and good compatibility with marine environments: Guo et al., 2021; low degradation is waterlogged environment: Levy., 1987). These materials (besides concrete) are largely colonised by crustaceans, mollusks and annelids (benthic communities), which are organisms preyed upon by the European eel (little et al., 1996).

The internal habitat area is filled with coir rope and fibre (Figure 22) because the eels seek out this material to shelter in (Klein Breteler., 2005; Results TRL 5 test, Chapter 5.4.2: WILD bijzonder vissen).

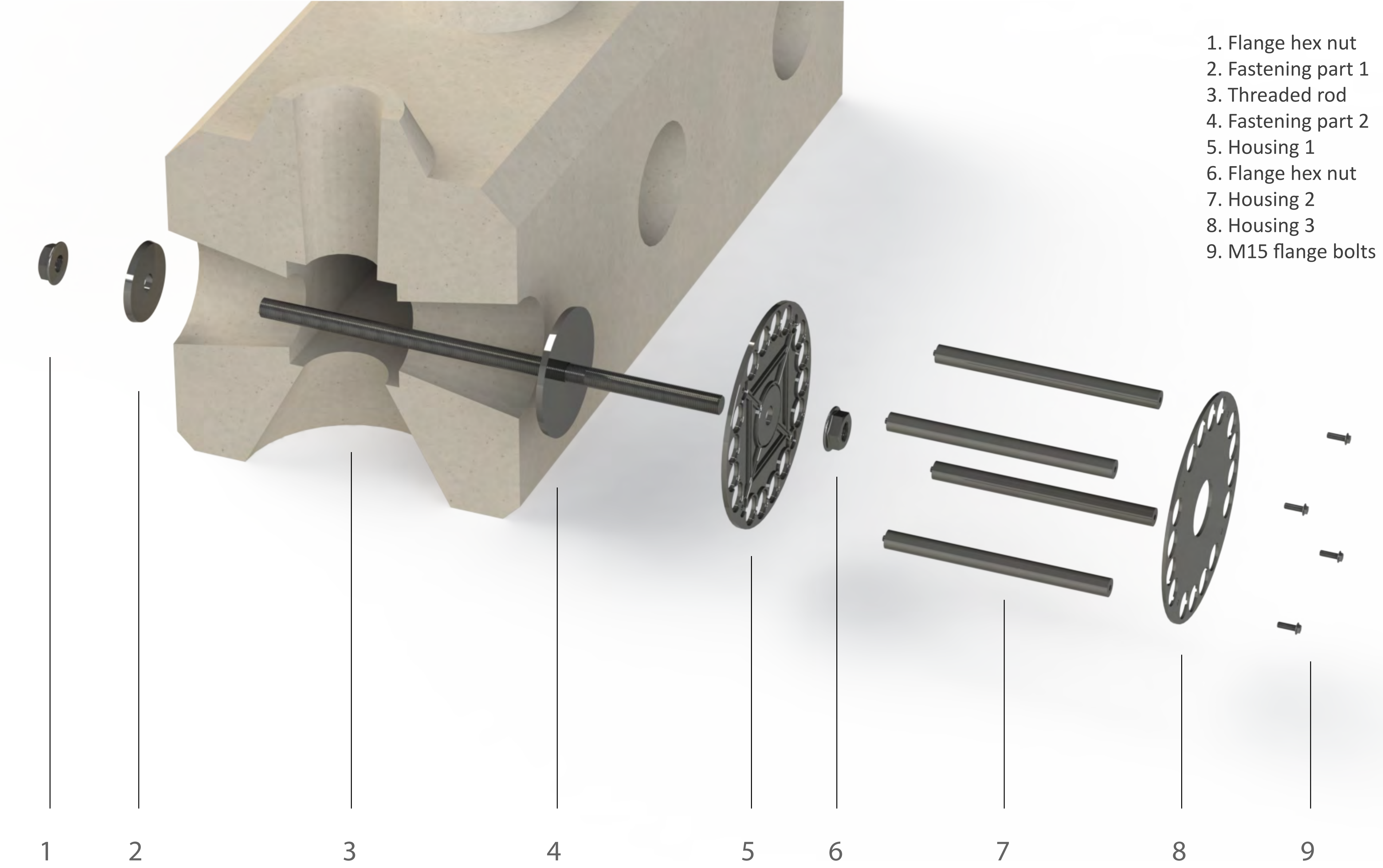
Figure 22: Coir rope and fibre

This design has focused on simplicity and low cost. Parts in the product can easily be developed or purchased as semi-manufactured products. A cylindrical shape was chosen to minimise resistance to wave energy, which increases durability.
The module's main components are tubes, which is not only ideal as an eel habitat but also makes scalability and customisability easy.

During my time at the startup Reefy, it was noticed that things are constantly changing. A modular design was therefore decided on. Should anything change to the geometry of the Reefblock or the EcoModule, only parts will have to be adapted/ replaced and not the entire product.

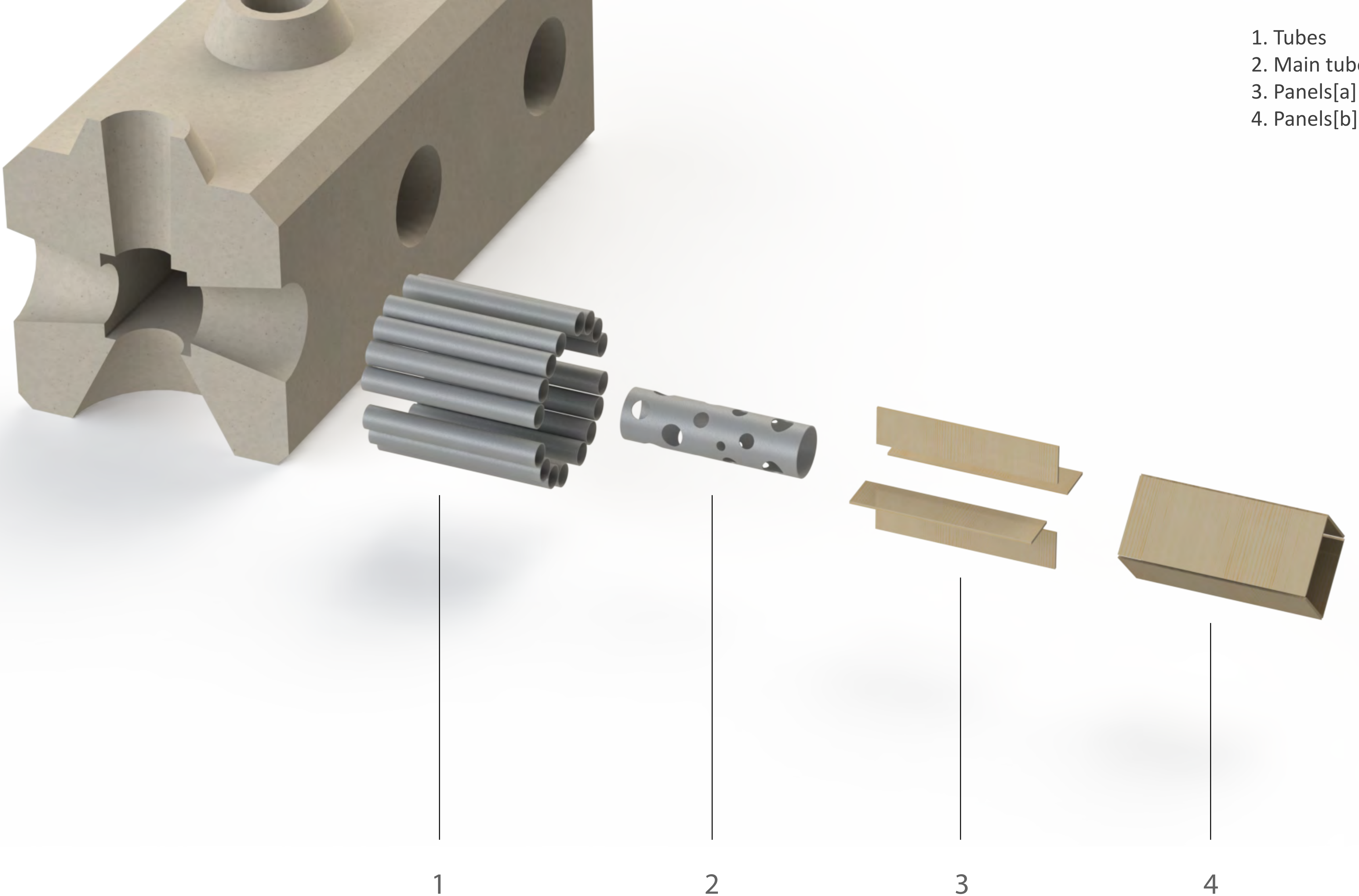


1. Flange hex nut
2. Fastening part 1
3. Threaded rod
4. Fastening part 2
5. Housing 1
6. Flange hex nut
7. Housing 2
8. Housing 3
9. M15 flange bolts



Structural parts

1. Tubes
2. Main tube
3. Panels[a]
4. Panels[b]

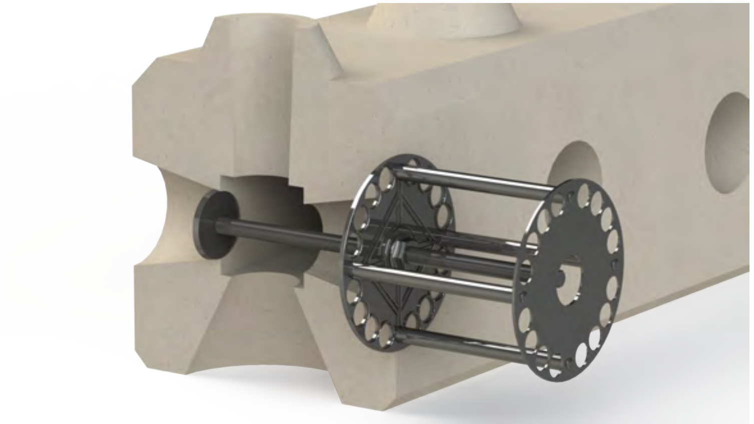


Non-structural/customisation parts

4.1 Module Breakdown

The EcoModule consists of structural parts; which provide the housing and attachment to the Reefblock (more information on Reefblock see Appendix 7) and of customisation parts; which provide classification of habitat areas in the product.

4.1.1 Structural parts



Housing 1
Diameter: 600mm; Thickness: 15mm
Material: recycled Q235 low carbon steel
Weight: 14,8 kg

This CNC-milled disc connects the module to the fastening method using the centre hole, Figure 23.

Figure 23: Housing 1

Housing 1 provides four sunken holes (depth 5mm, diameter 50mm) with four tapped holes (M15) for fastening of housing 2 (Figure 24). Tapped holes instead of bolts were chosen because the surface of this housing makes contact with the Reefblock and therefore has no room for a bolt. Countersinking the bolt could be an option, but would result in an increased thickness, which is detrimental to the weight and cost.

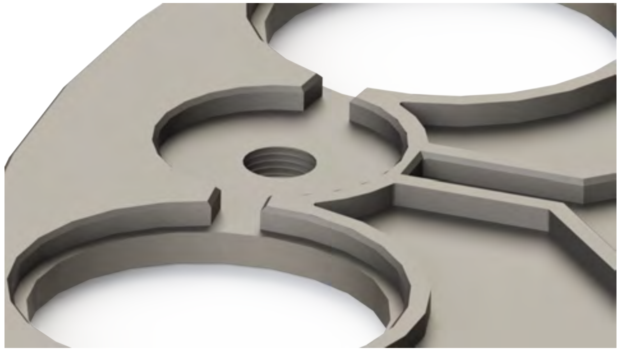


Figure 24: Sunken and tapped hole for fastening of housing 2

16 sunken holes (depth 5mm, diameter 80/74mm) offer space for clamping PVC tubes. Slits (depth 5mm, width 10mm) serve for both wooden panels and the main tube (Figure 25).

Figure 25: Sunken holes for PVC tubes and slits for panels/main tube

Unnecessary material is removed to reduce weight. Champfers have been placed where customisation parts are clamped in, which helps in the assembly process. The fillet corners created by CNC millinghave been taken into account.

Housing 2
Diameter: 50mm; Wall thickness: 3mm; Length: 590mm
Material: recycled Q235 low carbon steel
Weight: 2,3 kg

Four tubes connect housing 1 to housing 3. One side uses a thread which can be screwed directly into housing 1, the other side (fastening housing 3) has a tapped hole where an M15 flange hex bolt can be screwed in (Figure 26). Tubes (wall thickness 3 mm) are used instead of solid bars to save weight and cost (Figure 27). Welding sockets male and female are used to provide the ends with mounting parts, see Chapter 7.1: Feasibility.

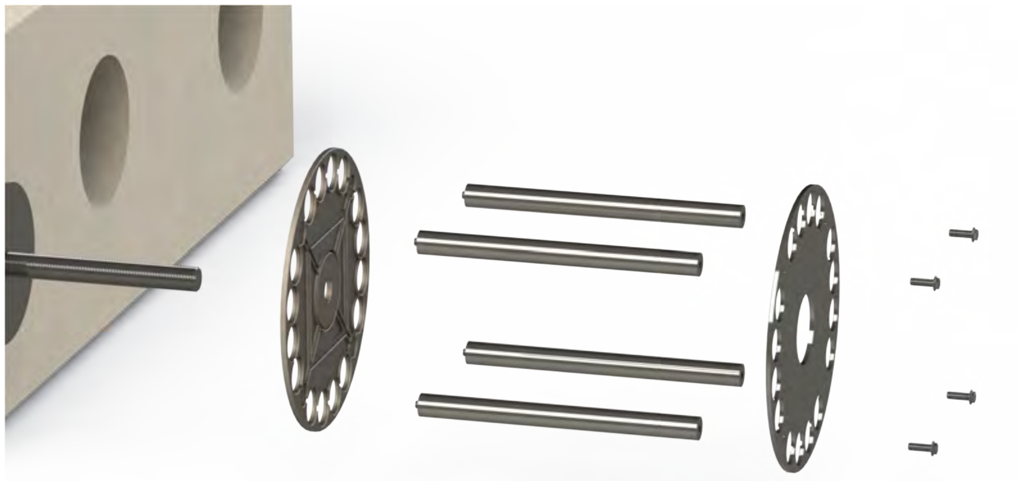


Figure 26: Fastening housing 2

Figure 27: Cross-section housing 2 tube

Housing 3
Diameter: 600mm; Thickness: 10mm
Material: recycled Q235 low carbon steel
Weight: 10,1 kg

This disc (Figure 28) originated from housing 1.
Three modifications have been made to this housing:
-Centre hole increased to 150mm. Creates main entrance of EcoModule.
-Removed tapped holes, beneficial for clamping using M15 flange bolts
-Removal of tapped holes allow decrease in thickness (15 to 10mm)

Figure 28: Housing 3

Fastening method

Fastening part 1
Diameter: 223/215mm; Center hole 50mm; Thickness: 20mm; Weight 5.95 kg
Material: recycled Q235 low carbon steel

Fastening part 2
Diameter: 350/342mm; Center hole 50mm; Thickness: 20mm; Weight: 14,4 kg
Material: recycled Q235 low carbon steel

Using a threaded rod (12kg), two tapered fastening parts and two flange hex nuts, the module is attached to the Reefblock (Figure 29).

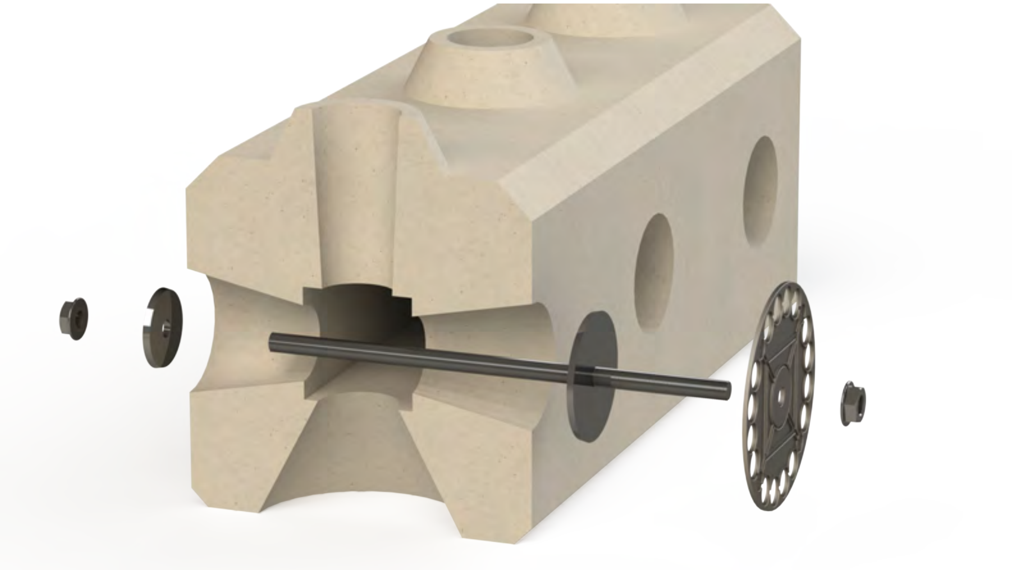


Figure 29: Fastening part

The threaded rod and flange nuts are standard parts that can be purchased. The minimum length of the threaded rod, needed for fastening the EcoModule, is 794mm. You could extend this part to 1300mm to allow for the attachment of additional components (such as separation components, Chapter 4.6: Customisability). The visualisation shows this extended rod, but it is not necessary. This threaded rod could also be replaced by a threaded tube, to save weight and cost. See Chapter 10: Recommendations.

The tapered holes of the Reefblock are designed with an angle of 11.31 degrees. A good fit of fastening parts 1 & 2 is essential. Both fastening parts therefore have the same angle as the tapered shape of the Reefblock (Figure 30). When fastening, parts 1 & 2 are tensioned towards each other using the hex nuts, frictional force is created between the tapered fastening parts and the Reefblock, creating a solid connection.

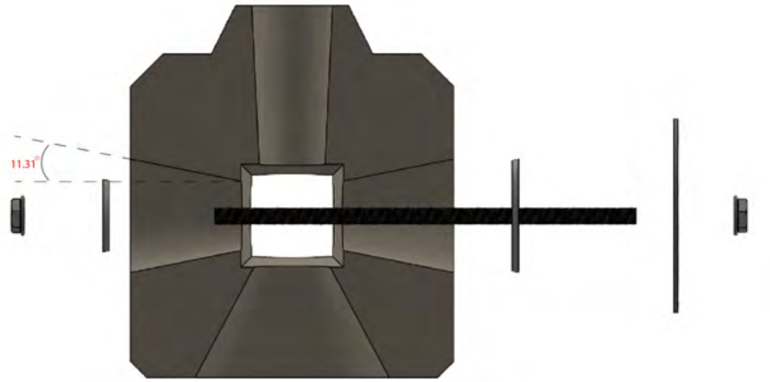


Figure 30: 11.31 degrees angle

Since concrete is a brittle material (Victor, 2020), you want to avoid applying a high force to a small edge, therefore fastening part 1 has increased in diameter which creates an offset (Figure 31).

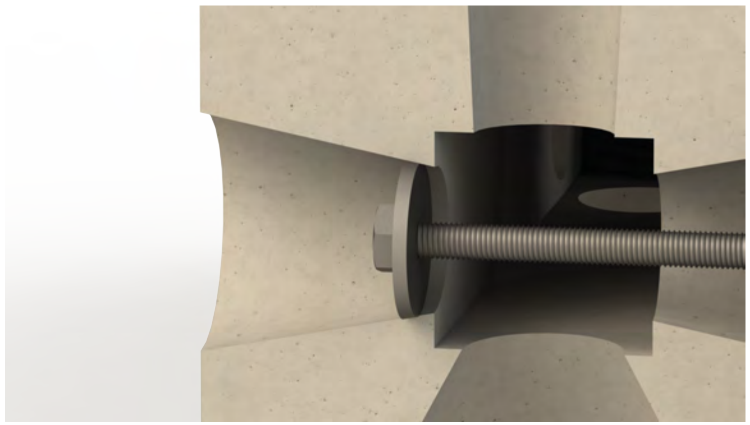


Figure 31: Offset

4.1.2 Customisation parts

This section discusses three customisation parts of the EcoModule: Main tube [1], Tubes [2] and panels [4]. All parts are placed in the sunken slits/holes of housing 1 & 3 with an exact fit. When housing 1 and 3 are tightened, these parts will be secured.

PVC and Populus wood are used in the eel configuration. These bioreceptive materials have a low cost and attract producer and consumer organisms that serve as food for the eel (benthic communities). Should another macro organism be targeted, a study will have to be done specifically on this species. However, Chapter 5.1.4: Materials, shows several suitable bioreceptive materials such as; Arboblend, basalt, terra-cotta, gabbro, solanyl and limestone that can be used in the EcoModule.

Main tube
Diameter: 150/146mm; Length 600mm
Material: Polyvinylchloride (PVC)
Weight: 1,7 kg

The main tube (Figure 32) is placed in the center of the EcoModule. In this tube there are holes that give access to other areas. This is considered the tube where several eels rest and are ready to attack prey. Should the eel prefer to hide or rest alone or in pairs or triplets it can use one of the other tubes.

Figure 32: Main tube

Tubes
Diameter: 80/74mm; Length: 600m
Material: Polyvinylchloride (PVC)
Weight: 0,38 kg

The tubes act as walls of the module and provide (internal) habitat areas at the same time. The test in the Eel pond (Chapter 5.4.2) showed that tubes with a diameter of 50-80mm are preferred. 80mm was chosen because it has been observed that several eels enter a single tube at the same time.

Figure 33: Tube

Panels
Panel [a]: 132x600x10mm, weight: 0,44 kg
Panel [b]: 256x600x10mm, weight: 0,83 kg
Material: Populus wood

Creates different habitat areas and have flat surfaces that can be colonised by micro organisms. Panel [b] has 45-degree, angled sides for a surface-to-surface fit.

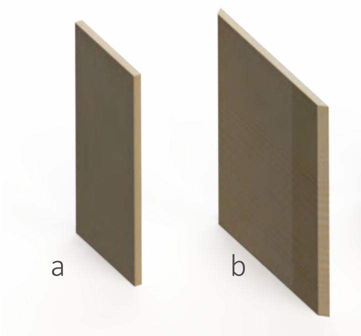


Figure 34: Panel [a]/[b]

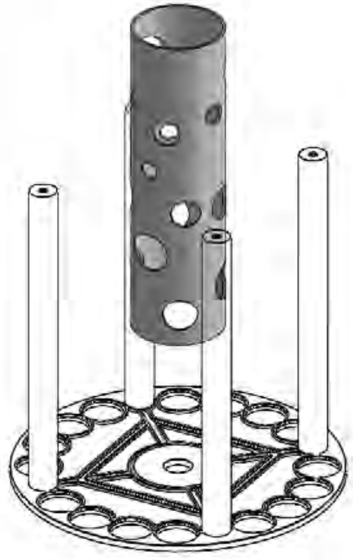
4.2 Assembly

See next pages for a step-by-step explanation on how to assemble and store the EcoModule.

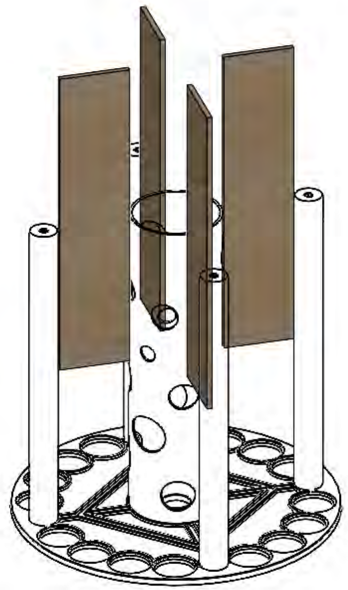
Place housing 1 on table or ground

Installation of tubes (housing 2). Rotate entire tube to fasten (tapped thread connection)

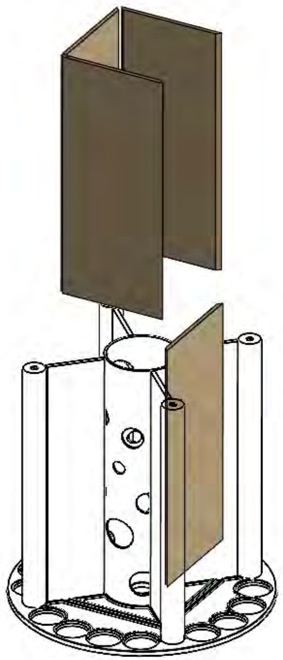
Installation of main tube (exact fit)



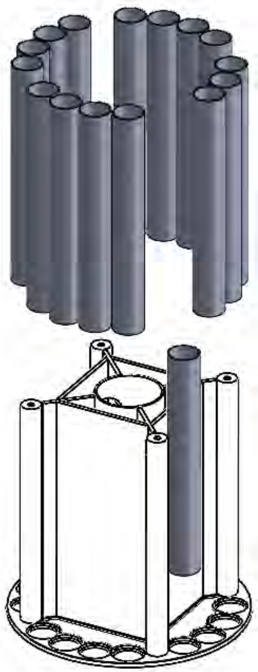
Installation of panels [a] (exact fit)



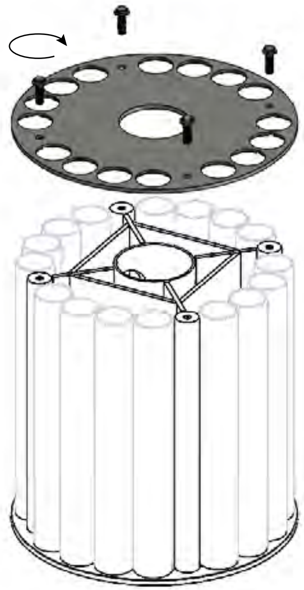
Installation of panels [b] (exact fix)



Installation of (pvc) tubes (exact fit)

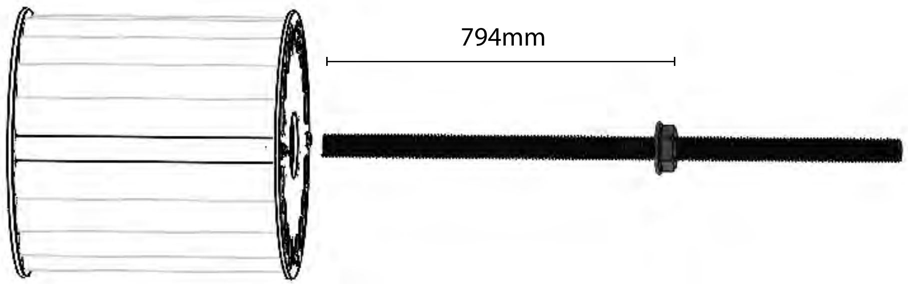


Installation of housing 3 to housing 2. 4 flange hex nuts to fasten en tension customisation parts

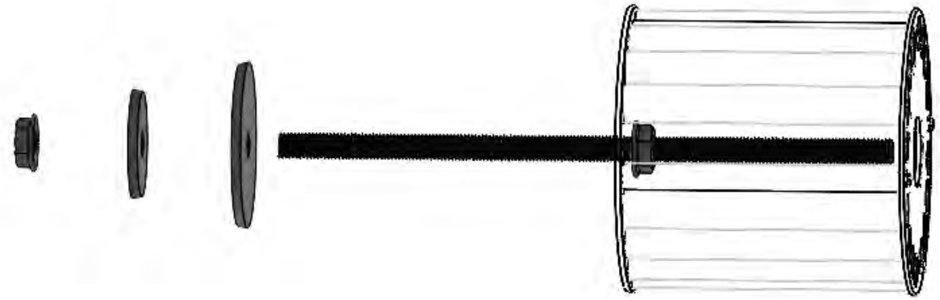


EcoModule except fastening method, turn sideways

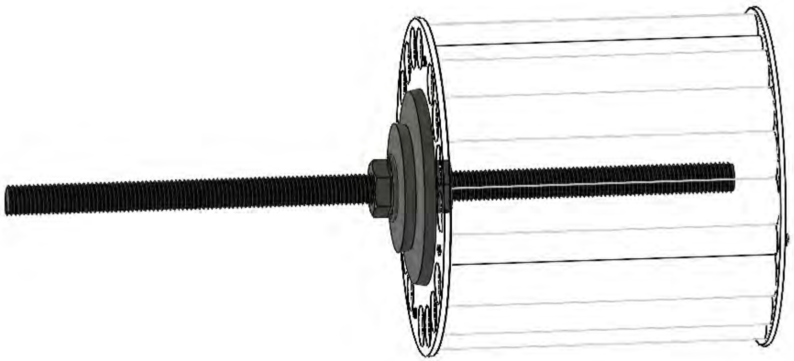
Screw nut on threaded rod. 590mm.



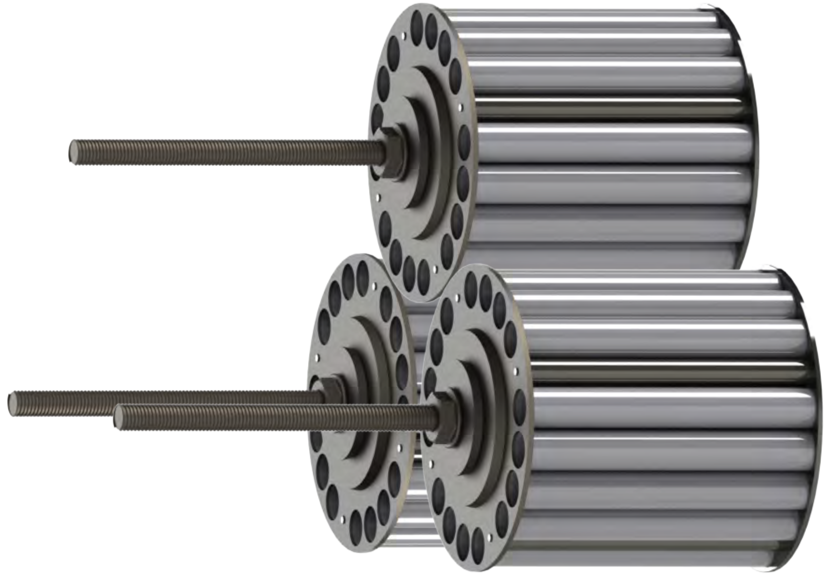
Place threaded rod in EcoModule. First slide big fastening part over threaded rod, followed by small fastening parts. Screw flange hex nut on rod to tighten all parts.



Fastening method installed.



Horizontal storage of EcoModules. Support trestles needed to prevent them from rolling. Preferred storage method (see next page).



Upright storage of EcoModule possible

4.3 Transportation

The EcoModule has a total weight of 88kg (including fastening method, 40.8 kg excluding fastening method). Multiple people will be needed to lift the module. Keeping the EcoModule sideways allows a single person to move the module through rolling

For lifiting, a fork lift is needed; using this machine, the module can easily be moved and loaded for transport (by truck) in the orientation shown below (Figure 35). The average dimensions of a transport truck are 2.55x4x12 metres (Evofenedex, n.d.), this means that the set-up below fits 20 times in one truck, resulting in 240 Ecomodules transported at ones. To ensure safe transportation. support trestles or tension straps are needed to prevent the modules from rolling/moving. The forklift also helps install the EcoModule to the Reefblock, see next page: 4.4 Installation

Figure 35: Set-up for transportation

A second method of transport is shown in Appendix 8. Here, the fastening method is transported separately and installed on site. This option could make transport cheaper however, installing the EcoModule to the Reefblock will be more difficult and take more time.

4.4 Installation to Reefblock

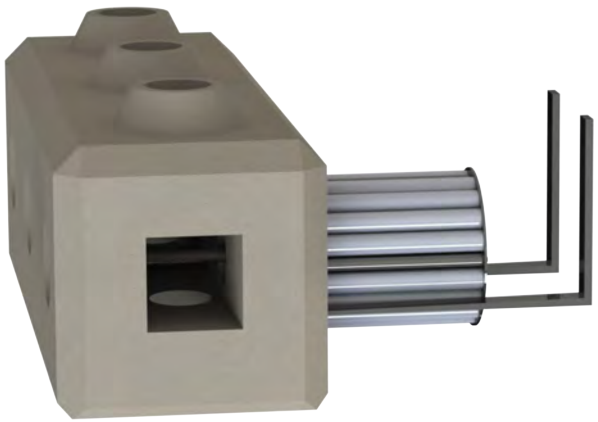
The EcoModule is delivered assembled, on site. The module is attached to a Reefblock on land. The Reefblock with the attached module is grasped as a whole by a crane, which then positions the module, with the help of software, in the right place in the REB.

See next page for a step-by-step explanation of how to assemble the EcoModule to the Reefblock.

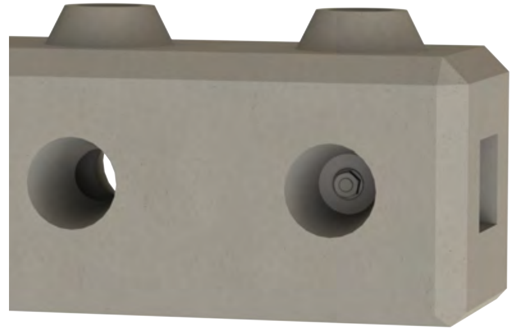
Forklift lifts EcoModule

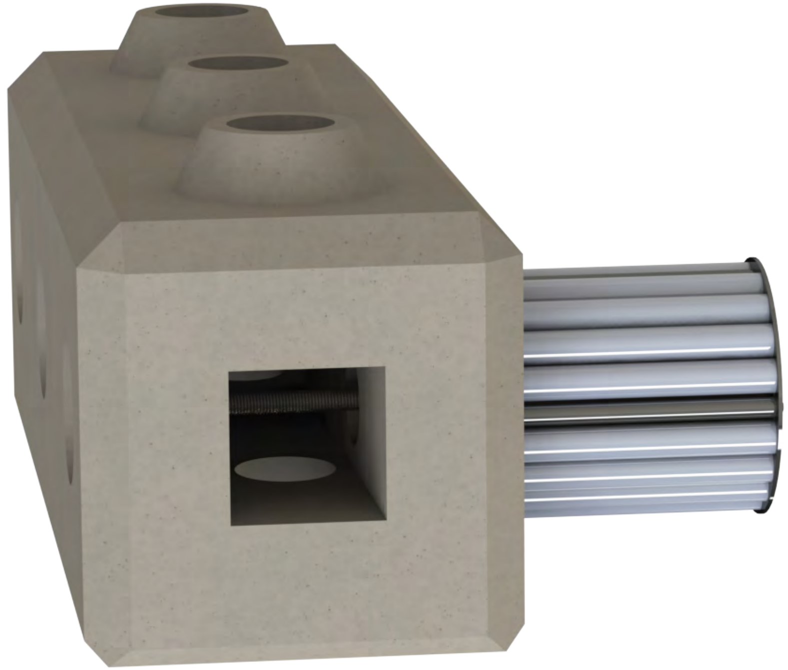
Flange hex nut and small fastening part removed

EcoModule is placed in one of the side tubes of the Reefblock. Fastening part slides over threaded rod, flange hex nut is screwed on



Apply force on flange hex nut to tighten the EcoModule.





4.5 Placement

The module is placed in one of the six tapared side holes of the Reefblock (Figure 36). The tapered hole mirrored to the position of the EcoModule is used for fastening. The reason for placing the Module on the side of the Reefblock is described in Appendix 6, Challenges.

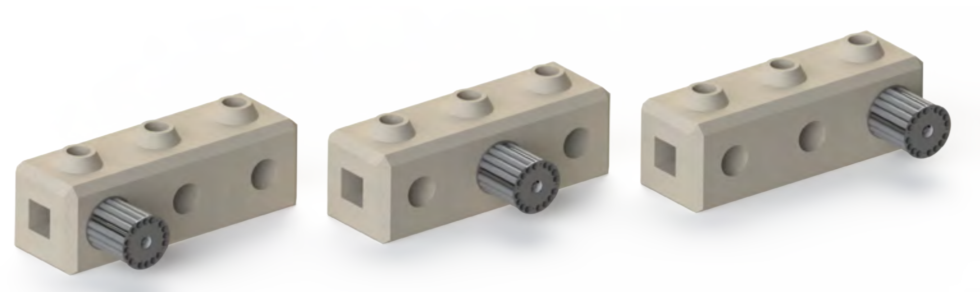


Figure 36: Possible position EcoModule

The EcoModule is placed on level 1 (lower layer of Reefblocks) or on level 2 in the REB (see Chapter 5.4.1: Deltares). Should the choice be made to place the EcoModule on the level 1, it is necessary to place this Reefblock in line with the flow direction (Figure 37). If the module is placed perpendicular to the flow direction, the module with the Reefblock will flip over (Results Deltares test), making placement of level two no longer possible.

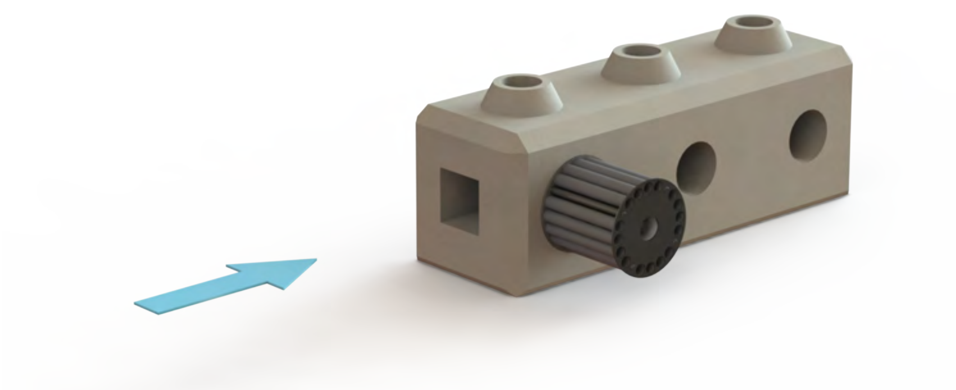


Figure 37: Reefblock with EcoModule in line with flow direction

The location of the EcoModule is determined by the targeted organism. One species prefers deep underwater, in the lee, while another prefers to rest, hide or reproduce in the current, off the bottom (Little et al., 1996). Figure 38 shows the preferred location of the module for the European Eel, close to the bottom, in the lee.

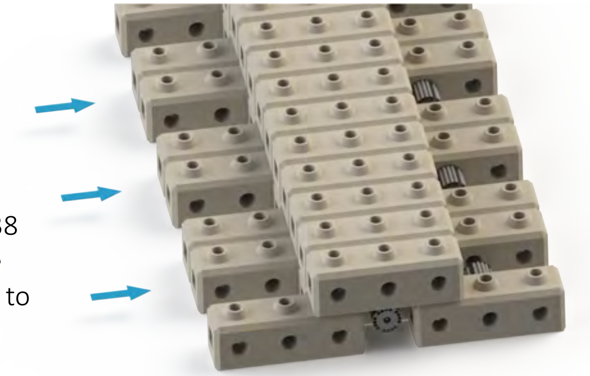


Figure 38: Preferred placement for the European Eel

As mentioned in the intro of the final design (Chapter 4), the EcoModule has a diameter of 600mm and a length of 600mm. Figure 39 shows that 600mm diameter is maximum because of the tapered shape on top of the Reefblock. If you make the diameter larger, the placement of the EcoModule becomes very dependent on the composition of the REB, many possible spots for placing the module are then dropped. The length is scalable up to 800mm. The length should not exceed 800mm as this increases the chances of a Reefblock hitting and destroying the EcoModule during installation.

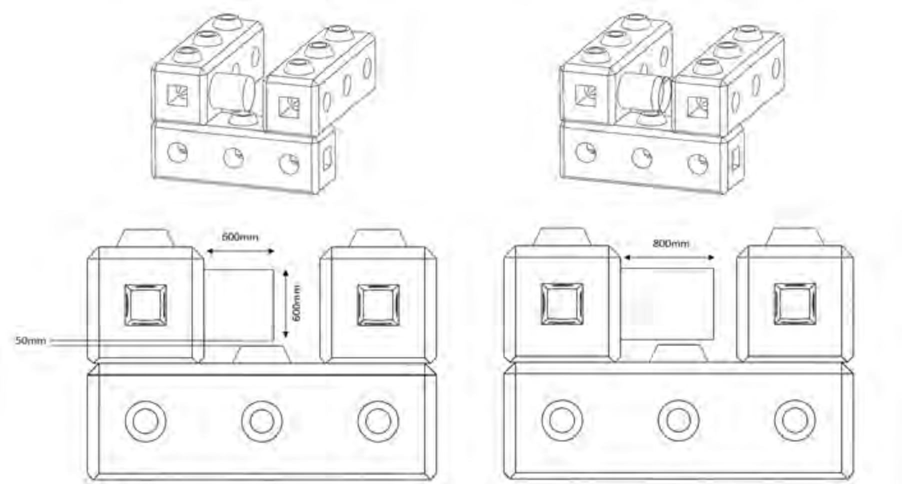


Figure 39: Dimensions EcoModule

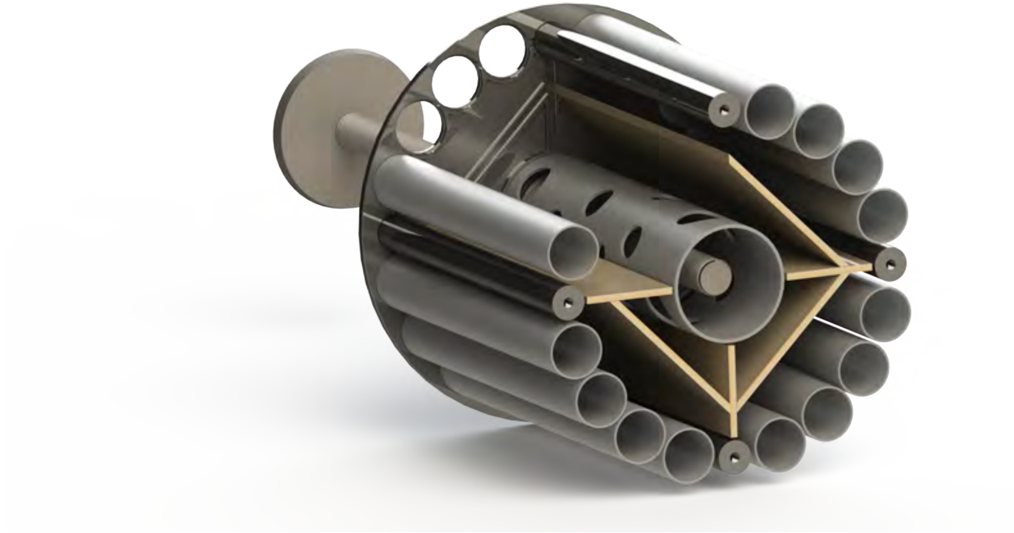
4.6 Customisability

Various aspects of the EcoModule have been discussed in the previous subsections. The components, assembly and placement of the habitat configured to the requirements of the European Eel were shown.

This section shows different configuration options of the EcoModule, which can be used for classifying a module according to the requirements of another marine organism.

Figure 40 shows that the internal components can be configured in multiple ways. The main tube and panels offer a variety of different configurations. These can be used to determine the number and volume of spaces in the module.

All materials visible are according to the configuration for the eel. However, because of the simplistic components in the design, these materials are easily adaptable to suit the needs of alternative organisms. Other materials, deployable for an artificial reef and suitable for the EcoModule are described in Chapter 5.1.4: Materials.



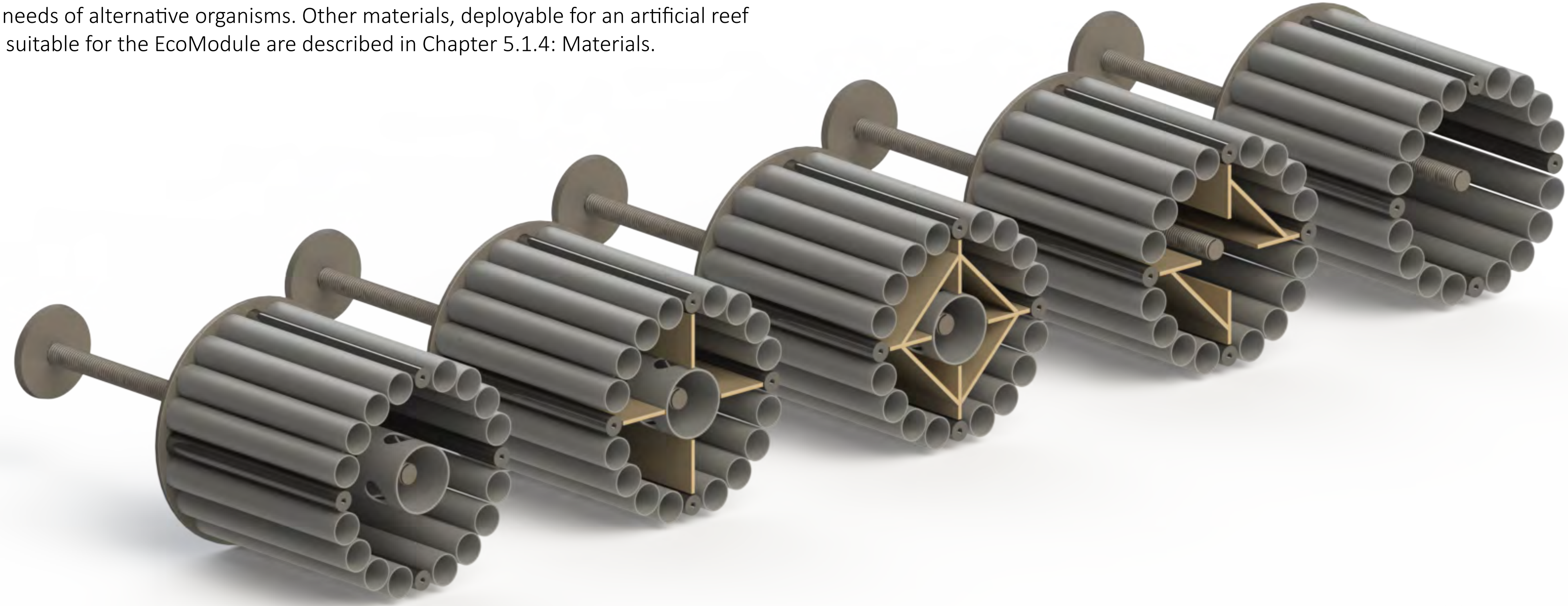


Figure 40: Internal customisability EcoModule

Not only can habitat be adjusted internally, more openings can be created by leaving out (PVC) tubes. Where there is an extra opening, the panels or main tube can be used to determine what this space looks like. In Figure 41[a], a large opening has been created that provide flat surfaces and gives access to the main tube and thus access to other spaces.

Figure 41[b] shows a self-contained habitat. A large flat surface made of wood that offers the possibility to be colonised. Figure 41[c] shows a habitat without partition panels. The habitat is divided into two large spaces (main tube and surroundings around it).

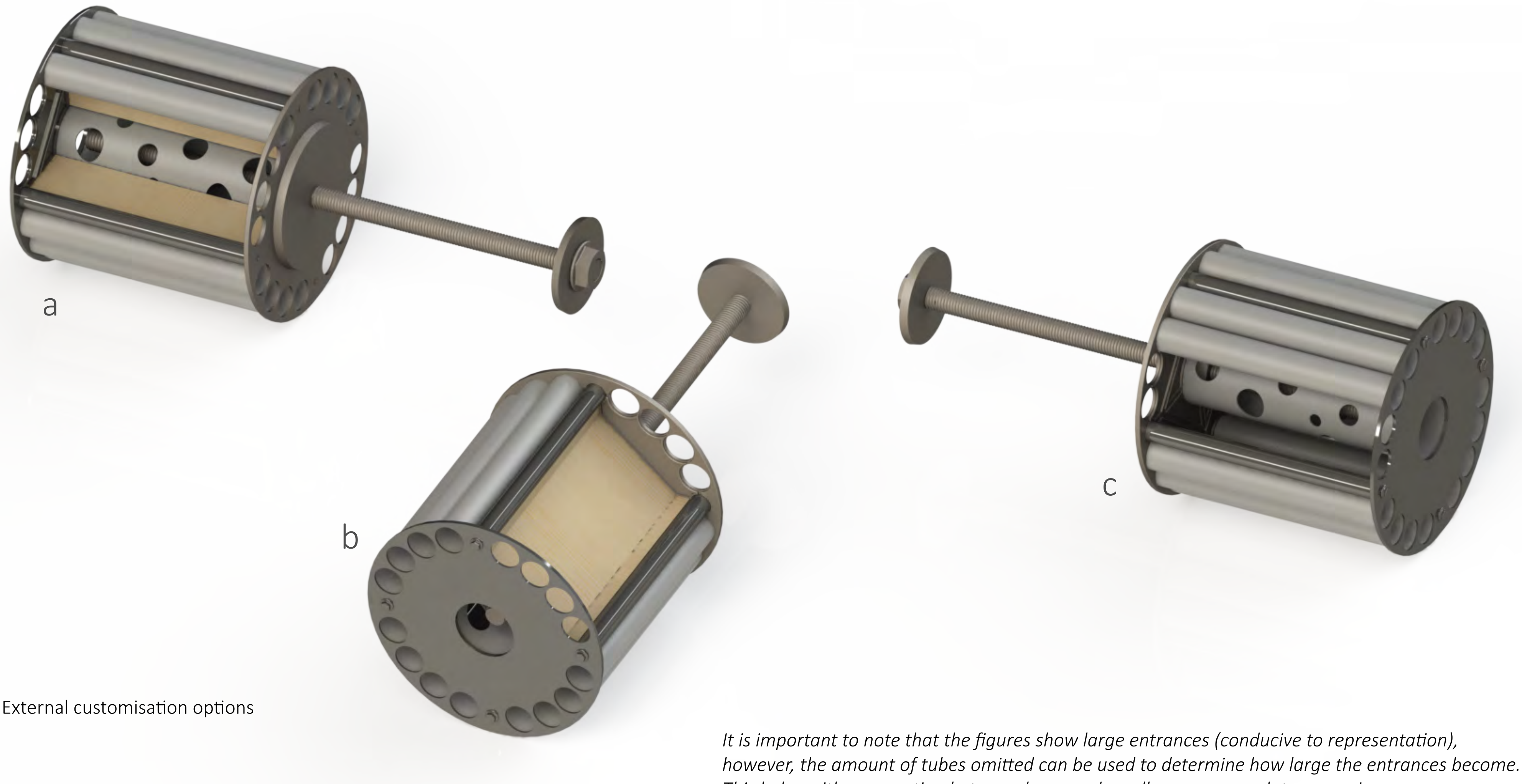


Figure 41: External customisation options

It is important to note that the figures show large entrances (conducive to representation), however, the amount of tubes omitted can be used to determine how large the entrances become. This helps with segregation between large and small grazer or predator organisms.

Extra options

Two components have been developed that provide additional options for customisation.

[1] Separation component
This component (Figure 42) can be placed anywhere, on the (extended) threaded rod. Two flange hex nuts are used to secure the component in place (Figure 43). The internal customisation parts can be cut to the desired length, offering the option of creating additional spaces (Figure 44). The (PVC) tubes slide through the separation component so do not change in length. This was chosen because this maintains simplicity, it can help with assembly and is desirable for the length of the eel (600mm). In case of a future design for another organism, shortening the tubes and tensioning using the separation component could be an option.

Figure 42: Separation component

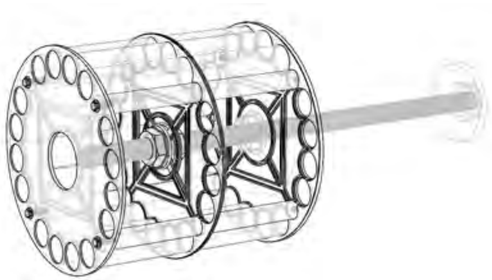


Figure 43: Fastening method

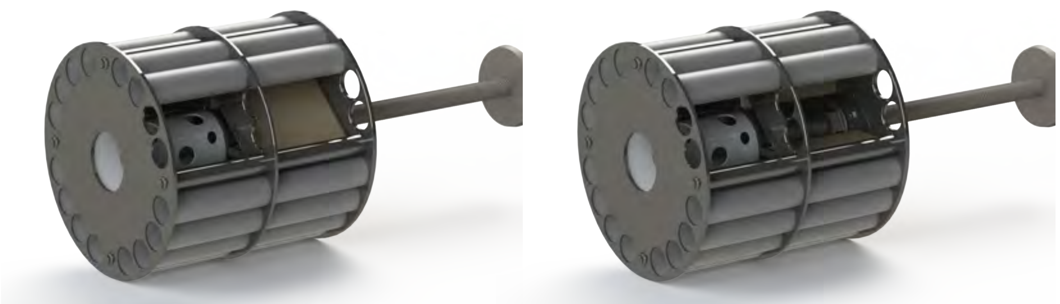


Figure 44: Additional habitat area's

[2] Enclosure panel
These panels (Figure 45) serve as a (bioreceptive) enclosure of the module that provides a large surface area to be colonised by micro-organisms. Also, this panel can completely seal a (large) space (to provide a dark environment) from the outside. The space can be entered through the holes of Housing 3.

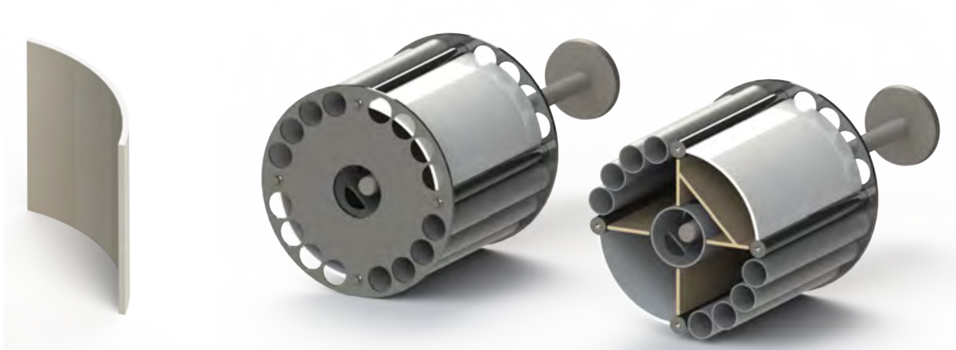


Figure 45: Enclosure panels

5. Design process and justification

5.1 Research

This chapter shows the design process from orientation phase to the final concept. Research was done on marine ecosystems, existing artifical reefs, the inital concept: The Ecoblock and materials that can be used for the EcoModule. Research was also done on the behaviour and habitat of the European eel, discussed earlier in Chapter 2: Case study on The European Eel.

5.1.1 Marine ecosystems

Distinction is made between different marine organisms; Shore, deep sea, pelagic and soft sediment organisms. This thesis focuses on shore organisms. On any coast, the diversity of marine organisms varies with vertical height. In general, diversity of macro-organisms is relatively low at the top of the coast and increases downshore because more species of marine plants and animals can live sublittoral, the area below the waterline that is always submerged (Little et al., 1996).

Since the EcoModule is placed downshore, it should be investigated which tropic levels of organisms (Figure 46) form an ecosystem foundation at this depth (producers and consumers) and which organisms are attracted to it and keep the ecosystem running (grazers and predators). Simply put, producers make their food from photosynthesis, producers are eaten by consumers, consumers are eaten by grazers and predators eat both grazers and consumers.

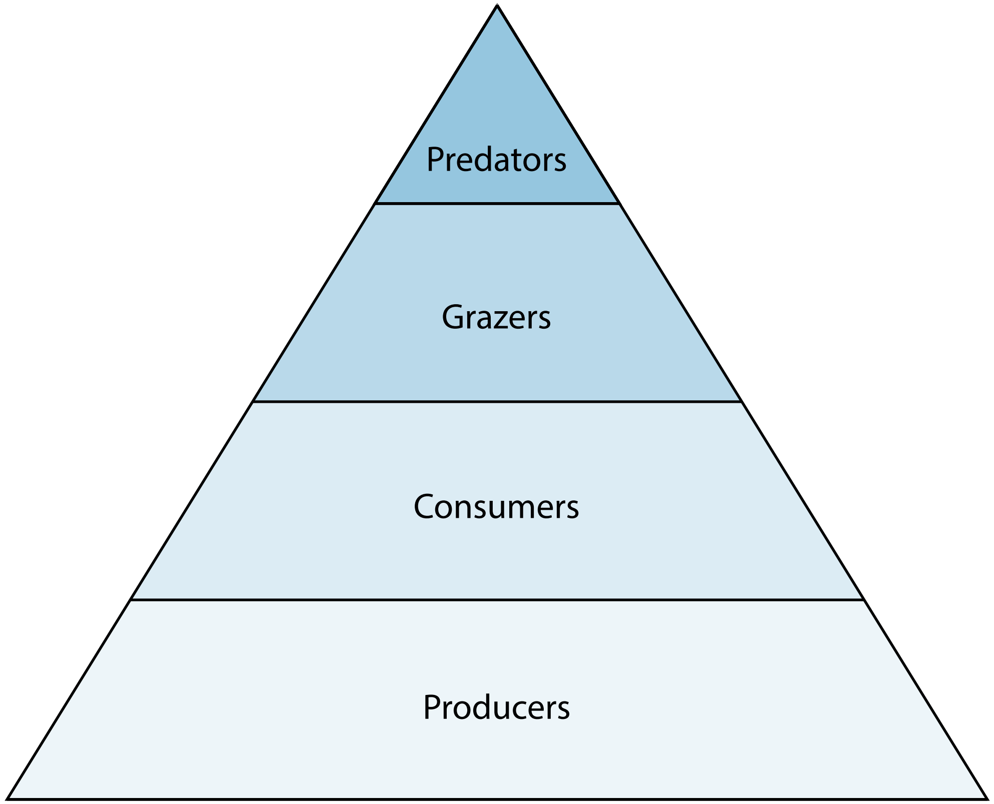


Figure 46: Trophic levels

Producers
All marine ecosystems depend on primary production. In most cases around shore ecosystems, these are (cyno)bacteria and algae. The algae can be divided into micro- and macroalgae. The most common microalgae is phytoplankton, a vegetable plankton that uses photosynthesis to survive (Little et al., 1996). However, in deep sea primary production is facilitated by chemosynthetic bacteria rather than photosynthetic organisms like phytoplankton (Vrijenhoek, 2010). Because this thesis focuses on shore organism, phytoplankton is considered the primary producer.

Consumers
Vegetable phytoplankton are eaten by animal plankton, zooplankton, a collective term for suspended/floating heterotrophic consumer organisms (organisms that obtain their nutrients from other organisms). Consumers include suspension feeders, in particular mussels and barnacles. Suspension feeding is the capture and ingestion of food particles that are suspended in water, these particles can include phytoplankton, zooplankton, bacteria, and detritus (dead organic material) (Hamann & Blanke, 2022). Producers and Consumers together provide the foundation for other marine species, called grazers and predators (Reynolds, 2006).

Grazers
Herbivore species that eat consumer organisms. They can be divided into four groups:

Sweepers; brush across the surface of rocks or macroalgea, sweeping up micro-organisms and detrital particles. Organisms: Topshells and nerites

Rakers: Dig into the surface of macroalgae, abrading it, picking up the resulting fragments of tissue as well as micro-organisms,. Organisms: Winkles, isopods, amphipods and grapsid crabs

Diggers: Abrade rock surfaces and scrape off the macroalgae. Organisms: Limpets, chitons and sea urchins

Biters and cutters: Bite of chunks of tough macroalgea (kelp) or chunks of rock. Organisms: (Parrot) Fish and majid crabs

Predators
Shore predators prey on grazers and consumers. Some of the predators are there all the time, while others visit only at particular states of the tide. Some feed on sedentary prey, others wait for mobile prey to come to them.

Predators can be divided into the following types:

Borers and drillers
Crushers and crackers
External digesters
Animal browsers or partial predators
Mobile vertebrate predators
Sit and wait
Parasites

The European eel is part of the category: Mobile vertebrate predators. These species hunt, accoording to little et al. (2005), crustaceans (barnacles), mollusks (mussels, limpets), annelids and invertebrates (all family of the benthic community). To lure eels toward the REB using organisms, materials colonised by the abovementioned consumers and grazers species will need to be used. These will be examined in Chapter 5.1.4: Materials

5.1.2 Artficial Reefs

Comparable projects have been studied to find suitable bioreceptive materials, get inspiration for the ideation phase and see how Reefy can differentiate itself from these projects/competitors. Listed below are several projects from which main takeaways have been extracted that helped develop the EcoModule.

Arcmarine

ECOncrete

Reefballs

Reef design lab

Living seawalls

Leaf global

Sculptures

MOSES

Oyster reef

Most used material: Concrete
Concrete is used for artifical reefs that are constructed as a single unit with large wall thicknesses. This is evident in the projects: Reefballs, MOSES, ECOncerete, Oyster reef, Arcmarine, Leaf Global and Sculptures. What is noticeable in all projects is that one type of artificial reef is designed, which is placed multiple times and thus offers no differentiation. Reefy is also currently doing this with its Reefblocks.

Design strategy: Concrete can be used as non-strucutral parts due to its bioreceptive properties. But not as structural parts because the material is brittle at low wall thicknesses. Thereby, because of the Reefblock, a lot of concrete is already present.

Standard, large habitat spaces
Several projects offer habitat space inside the objects of the artificial reef. However, these are very standard and large (Acmarine, Reefballs, Leefglobal). The artifical reefs provide access for a very large range of organisms (Reefblocks also provide this), which is not a bad thing but marine species cannot properly distance themselves from other organisms. There are no segregation possibilities

Design strategy: Design a housing that can be divided into different habitats where a specific species can distance itself from the rest. This creates resting, hiding and reproduction spaces.

Simple shapes, complexity lies in textures
In general, complex shapes are not used (except for Reef design lab). This makes production techniques easy and cheap. The disadvantage is that there are no, single habitats but only one large habitat. The complexity of artficial reef projects is found in textures (living seawalls ECOncrete, Reef design Lab, Arc marine), these are mainly developed for micro producer and consumer organisms. Textures are not within the scope of this project but can be added at an iteration step in the future (Chapter 10: Recommendations).

Design strategy: Keep the design simple, affordable, but make sure the product stands out from other projects by differentiating in size of habitat area.

No enclosed spaces
Every internal system of artifical reefs is open on all sides (same as with the reefblocks). This means there are no enclosed spaces. Organisms can be attacked from all sides (except when they have settled on a (textured) wall). Some (grazer /predator) organisms want to be protected from behind, for example the crab, this species defends itself with its claws that are located on the front of its body, so the crab is vulnerable at its rear.

Design strategy: Give the possibility to create enclosed spaces. This expands the amount of organisms you can provide with a habitat.

No additional fill materials are used
The artificial reefs are not filled with material that organisms might like to shelter in. The (assumed) reason for this is that it disappears immediately due to the sea currents.

Design strategy: Make use of fill material, but make sure it is confined in an enclosed space with small openings.

5.1.3 The Ecoblock

During the research phase, the Ecoblock was examined. This chapter describes the limitation that were found.

Although the design of the Ecoblock (Figure 47) was still at an early stage and only an MVP (Figure 48) is tested, a few limitations stood out:

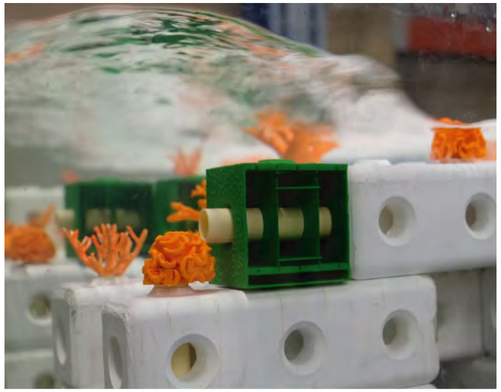


Figure 47: Ecoblock concept

Figure 48: Minimal Viable product

- Shape limited to a block (high resistance, high chance of break down)
- Improper attachment method, MVP broke down, low durability
- Dimensions 800x800mm
- One configuration, not customisable
- Feasibility not investigated, high investment cost for manufacturing one whole
- No validation
- Sustainability not taken into account

The above limitations were translated into requirements (Appendix 5) and considered during the design process. For clarification on how each limitation was addressed, see Appendix 9.

5.1.4 Materials

As discussed in the Chapter 1.1: Project context, the primary function of the product lies on developing additional habitat space for grazers and predators. Attracting these organisms is easier with a habitat that looks natural and a habitat that offers food (colonised micro-organisms). For this reason, the habitat was chosen to be made out of a bioreceptive material.

Multiple suitable bioreceptive materials for artficial reefs and the EcoModule were investigated (full research see Appendix 10). From this research, three materials were chosen that are most suitable for the EcoModule configured for the European Eel.

Q235 low carbon steel

According to Zhang et al (2008), microbial organism colonise on both carbon steel and on the layer of rust formed when submerged for a long period of time. In this test, copper, aluminium and carbon steel (q235) were compared. Biofilm forming organisms dominated the surface of carbon steel (Figure 49). Complementing this is a study on the colonisation of carbon steel structures. In this study, it was proven that the colonisation of organisms creates a biofilm that protects steel from corroding (Southwell et al., 1974).

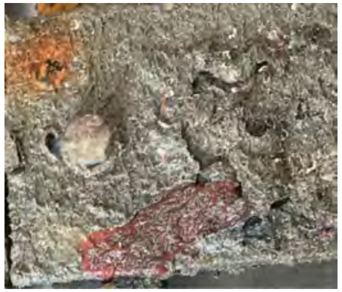


Figure 49: Surface biofilm on carbon steel plate

The use of Q235 steel is ideal for the structural parts of the EcoModule because it is strong, suitable for construction and engineering structures, has low cost and has a high durability (Emma, 2021).

Polyvinylchloride (PVC)

The use of PVC in artificial reefs is possible. Accoording to Brown (2005), PVC, along with concrete, scores high in terms of microbial colonisation; crustaceans, molluscs, annelids and bryozoans were found on the PVC surfaces. Steel, wood and rubber were also tested in this study. Colonisation on rubber was lowest, while steel and wood scored average. Complementing this, Vess et al. (1992), proved that water bacteria can colonise the surface of PVC pipes and develop signifacnt resistance to the action of certain germicides

Also, Co-founder of Reefy, Leon Haines, has built PVC structures (Figure 50), demonstrating that microbial organisms colonise this material over a time period of 2-6 months (Figure 51).

Figure 50: PVC structure

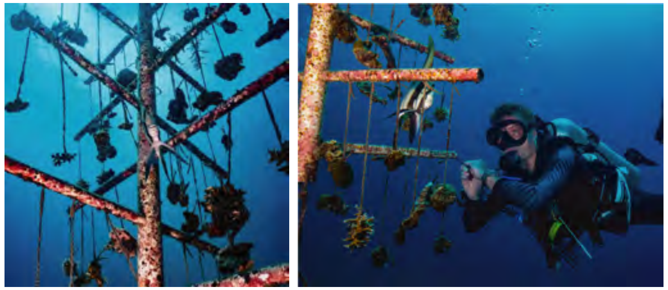


Figure 51: Microbial surface colonisation on PVC after 6 months

PVC is widely used as underground (drinking) water infrastucture because of its high durability, corrosion resistance, low cost and easy installation. According to Folkman (2014), the average lifetime of a PVC pipe is 47 years. This study showed that PVC pipes used for 20-49 years still pass the initial quality tests, meaning that the (micro) degradation of PVC is very low.

Micro plastics is currently a hot topic, however, it has been proven that a very low amount of microplastics has been found in drinking water, from water sources, which is a negligible amount for humans (Mintenig et al., 2019). This also proves that if PVC will degrade over a very long period, the amount of 'plastic waste' is negligible.

Populus wood

Wood is widely used for artificial reefs because of its low cost, lack of toxicity and good compatibility with marine environments (Guo et al., 2021). This study investigated whether microbial communities, groups of microorganisms that share a common living space, colonise the materials concrete and untreated wood (Populus). This test showed that concrete was the most colonised and wood matched it. For some micro organisms, such as benthic communities, the results were similar, which is ideal for attracting the Eel (Chapter 5.1.1 Marine ecosystems).

The degradation of wood in salt water is largely caused by contact with oxygen, wood-decaying organisms thrive primarily on the water surface, where there is an abundance of atmospheric oxygen, soil moisture, and nutrients available (Levy, 1987). However, when the wood is in a waterlogged/aquatic environment, degradation will proceed at a slower rate and will therefore survive for an extended period of time.

Other suitable materials:

Basalt
Gabbro
Terra-cotta
Solanyl
Arboblend
Limestone (created from dissolved minerals using electrified steel, Figure 52)

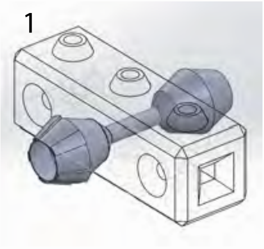
Figure 52: Biorock, electrified Reef

These materials were identified during the study as suitable materials for artificial reefs and could be used in the EcoModule. In order to use any of these materials, more research needs to be done on which organisms colonise these materials, based on this it can be determined which marco organisms can be attracted.

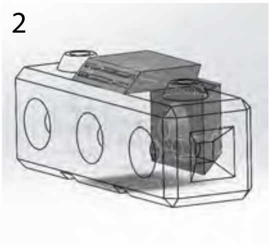
5.2 Ideation and concept choice

According to research, requirements (Appendix 5) were set-up, supplemented and adjusted during the process, and challenges (Appendix 6) were encountered.

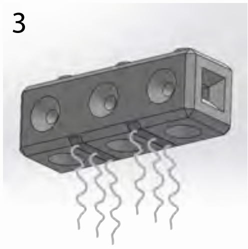
This chapter schematically represents the ideation phase up to the first milestone of this design process. Each idea is discussed individually in Appendix 11.



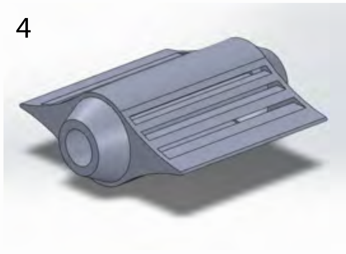
SHAPE



GRID



SIMPLICITY



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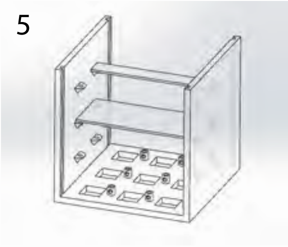
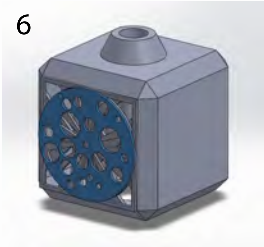
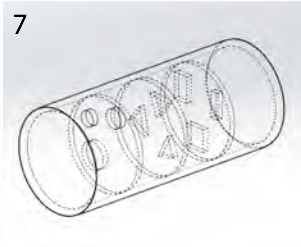


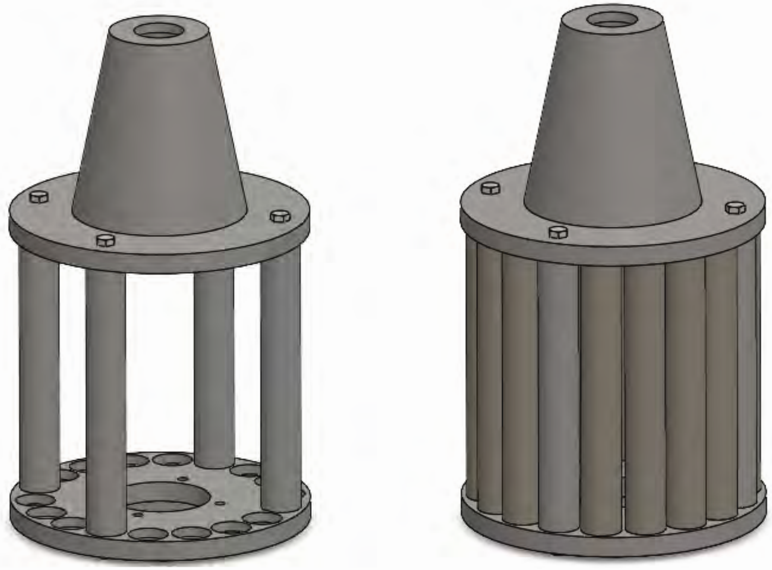
CUSTOMIZABILITY



DISCS/TUBES

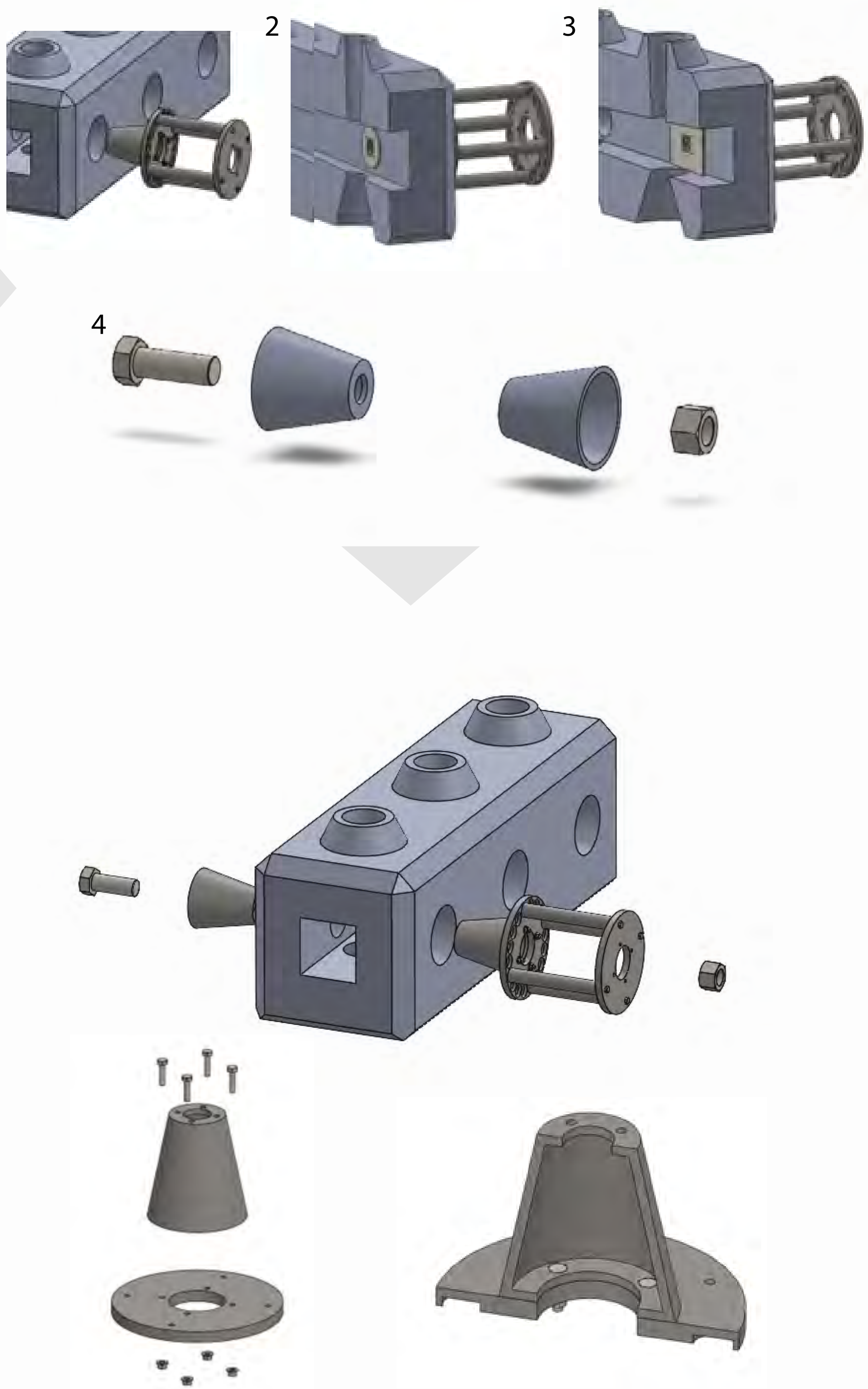


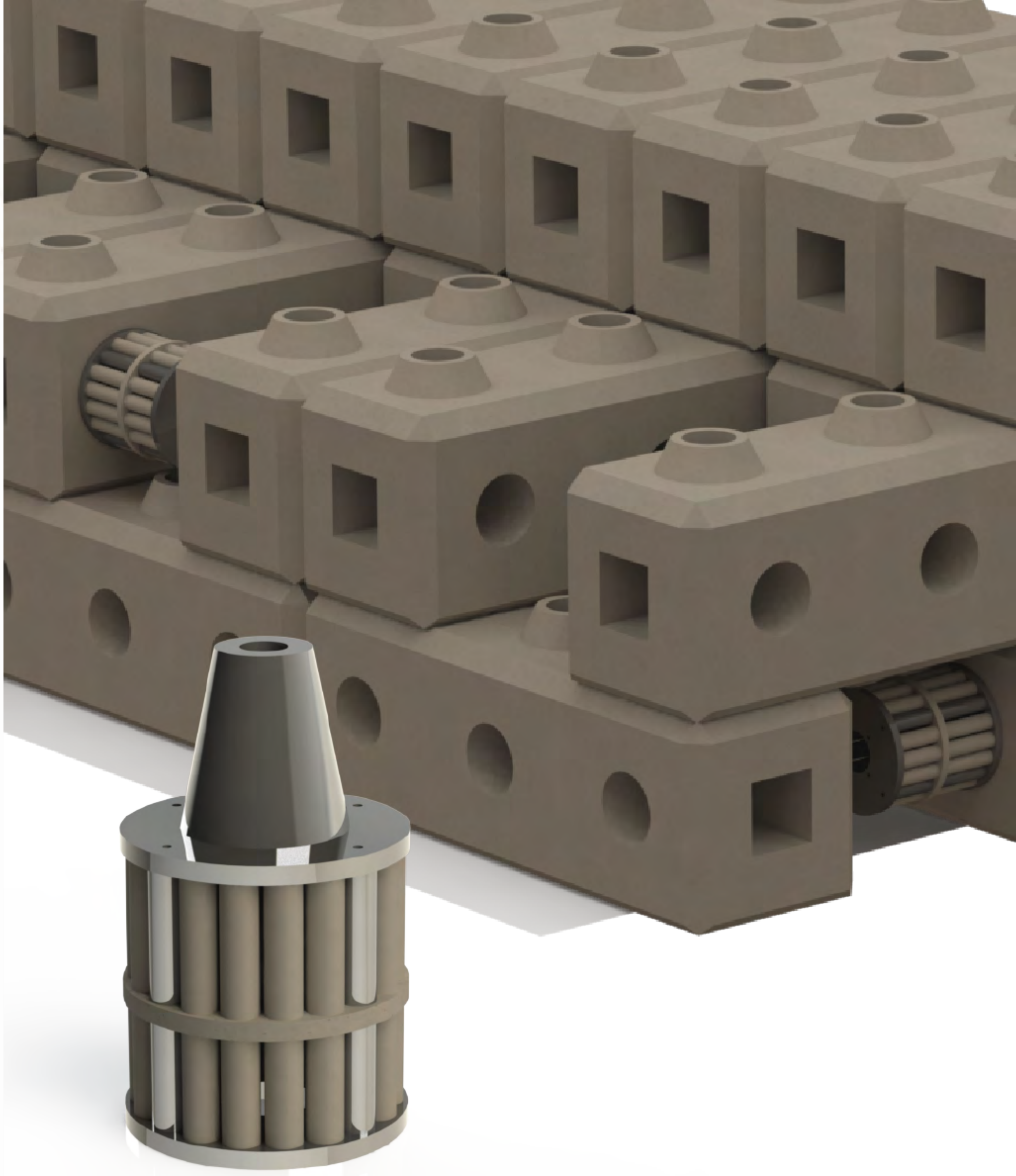
SHAPE/DISCS



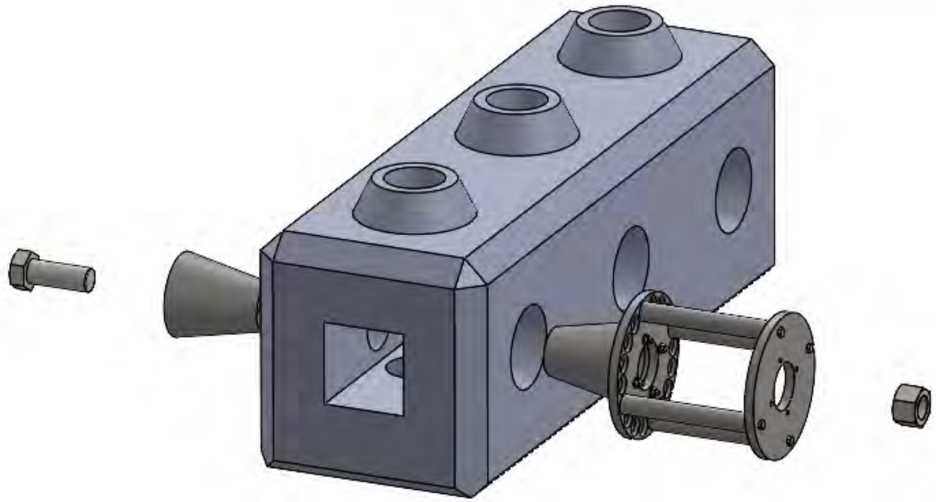
Module

Fastening method





Concept choice (milestone)



5.3 Prototypes

A design direction has been chosen. This milestone led to several prototypes to further develop the concept.

This chapter describes the main takeaways extracted from the developed prototypes. These takeaways were seen as new insights and challenges emerged that were taken into account in the development of the final design.

1:20 scale prototypes created for testing at deltares

For the test at deltares, four simplified versions of the EcoModule including fastening method, in scale 1:20, were developed (Figure 53). The prototypes were made out of four different materials: Steel, concrete, wood, PLA (plastic). The material did not influence the tests carried out at Deltares, but the different materials provided insights into material properties and manufacturing techniques. How these takeaways influenced the development of the EcoModule are described in Chapter 5.5 Detailing of concept choice.

Figure 53: 1:20 scale prototypes

Main takeaways prototypes:
- Steel tapered fastening method- Strong, easy to assemble
- Brittle concrete, drilling a hole in concrete was not possible, breaks down at low wall thickness
- Hollow fastening method felt fragile

1:1 scale prototype created for testing at Eel pond

A 1:1 scale prototype (Figure 54) was developed for testing in a relevant environment (TRL 5). Building this prototype required good preparation with the goal of easy assembly of the product.

The prototype was constructed from two wooden disks, four wooden rods and seventeen PVC tubes with different diameters. Two wooden panels were made to divide the module into four compartments. Eight screws were used in the product to hold all the parts together using exact fits, sunken holes and slits.

Laser cutting was used to develop the disks for which .dxf drawings were developed (Appendix 12), this gave the first insights into making sunken holes, exact fits and how to assemble the product. Also, a pedestal has been developed to mimic the floating effect (when fastened to Reefblock) of the EcoModule

Figure 54: 1:1 scale prototypes

Main takeaways:
- Preparation a lot of work, assembly of the product in very little time
- Very strong construction despite using only four screws per side.
- Housing discs mirrored relative to each other resulted in a design fault, making the discs symmetrical prevents this.
- Placement of last disk was hard due to non-alignment of tubes, a partition/ component could help with this but is not necessary

5.4 Testing

5.4.1 Deltares

Deltares, a technological institute in the field of water, subsoil and infrastructure has facilitated a wave simulation flume (Scheldegoot, Figure 55) to conduct tests with the EcoModule and the Reefblocks. The Reefblock are constructed as REB and go up to a maximum height of three levels (Figure 56).

Figure 55: Scheldegoot Delateres

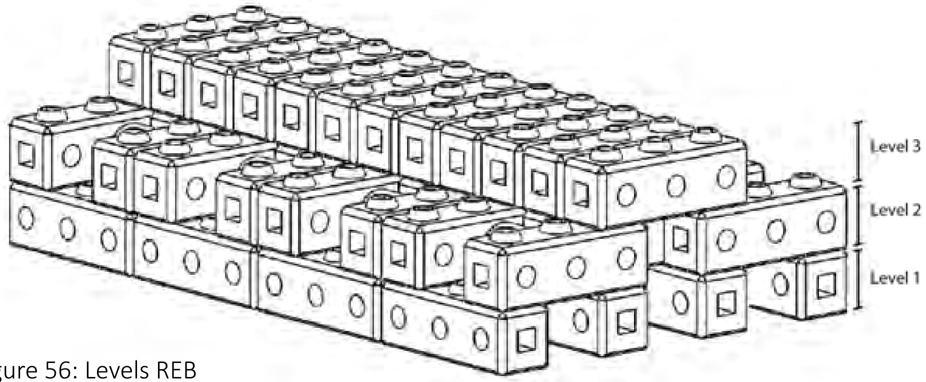


Figure 56: Levels REB

Important to mention here is that the EcoModule will never be placed at level 3, because this could possibly cause the EcoModule to come above water. One of the requirements states that the EcoModule will always remain watterlogged, this requirement is set up to prevent deterioration and it is not pleasant for grazers or predators to come above the water when they are resting or hiding in the habitat.

The REB is placed in the simulation flume, on hydraulic bricks (ensuring a flat surface). The Reefblocks are scaled 1:20, in which the density of the Reefblocks remains the same. 3D printed molds are filled with concrete and steel pellets to achieve the same density as the 1:1 Reefblocks. The test flume is set to mimic reality in a 1:20 scale.

Two different tests were performed to determine if the EcoModule could be placed in both Level 1 and Level 2 of the REB

Test 1: Influence on single Reefblock (Level 1)

This test compares a single Reefblock with and without the EcoModule. In test 1a, the Reefblocks are placed in the orientation along with the wave current (Figure 57). In test 1b, the Reefblocks are placed in the orientation perpendicular to the wave current (Figure 58).

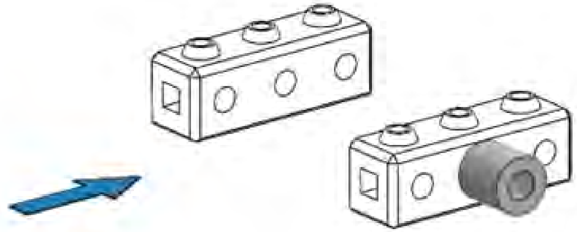


Figure 57: Orientation along with the wave current

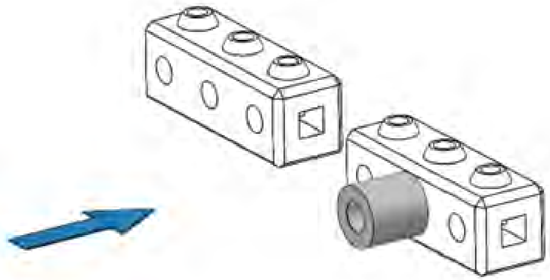


Figure 58: Orientation perpedicular to wave current

It is observed whether the EcoModule affects the stability of the Reefblock. The reason for attaching the EcoModule to a single Reefblock is important when installing the REB. When level 1 is installed, the Reefblocks are placed individually onto the seabottom. Should the Reefblock rotate or move, it is not possible to install level 2.

Results test 1
The observations showed that in test 1a, oriented along with the wave current, both blocks remained stable. In test 1b, it was observed that the Reefblock with EcoModule immediately flipped backwards and turned upside down (Figure 59). The Reefblock without EcoModule remained stable in this orientation.

Figure 59: Result orientation perpendicular to wave current direction (in the figure from left to right)

Conclusion test 1
When installing the Reefblock with EcoModule on level 1, it is important to place it in the orientation along with the wave current, as shown in Figure 60.

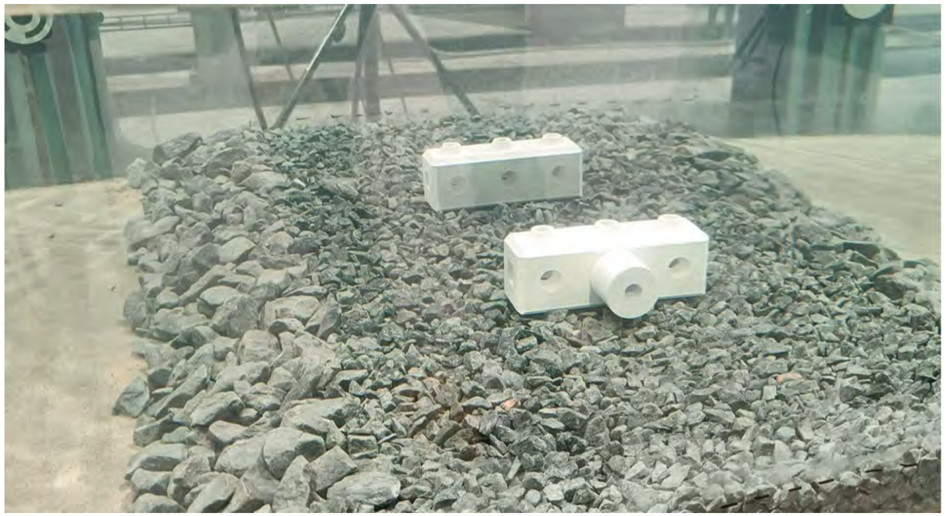


Figure 60: Orientation along with wave current direction (in the figure from left to right)

Test 2: Influence on Reefblock in REB (level 2)

During the test with the EcoModule, two levels of the REB were constructed. The composition of the Reefblocks used for testing is shown in Figure 61.

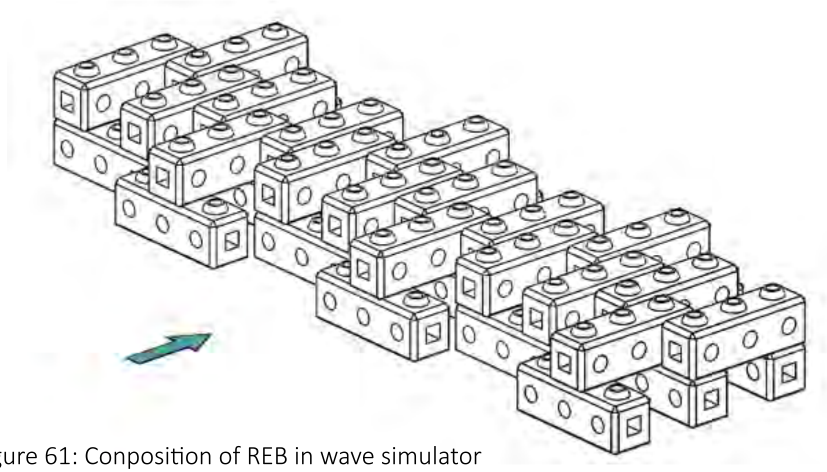


Figure 61: Conposition of REB in wave simulator

The scale prototypes were attached to the Reefblock (Figure 62) using the chosen attachment method shown in the concept choice milestone (Chapter 5.2: Ideation and concept choice).

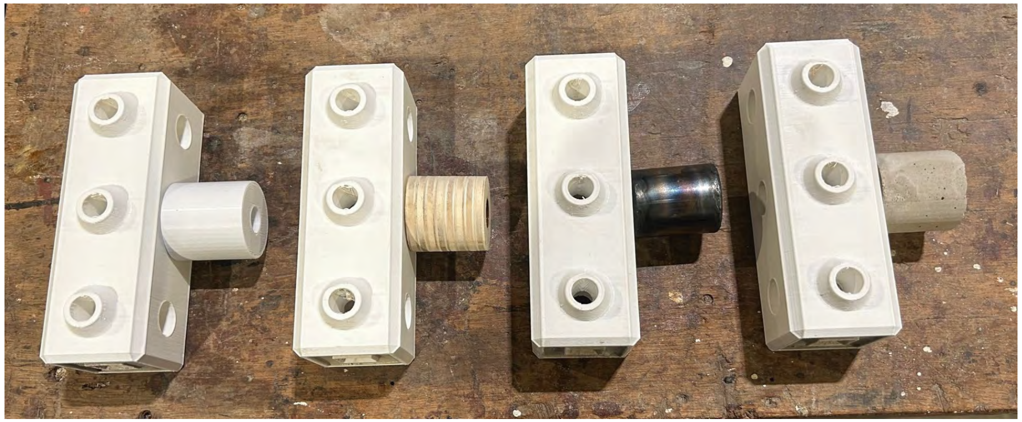


Figure 62: 1:20 test prototypes

The prototypes were placed in four locations, at level 2, in the REB. Two at the front and two at the back seen from the wave current direction (Figure 63). The test investigates whether the EcoModules affect the stability of the Reefblocks. Results were obtained from observations.

Figure 63: Four 1:20 prototypes in REB (wave current direction from left to right)

Results test 2

Observations prove that the Reefblocks with EcoModule do not move more than Reefblocks without EcoModule. Once in a while, a miniscule movement could be seen, however, this movement is negligibly small and therefore will not have a negative impact on the REB.

Conclusion test 2

It has been proven that the EcoModule can be placed on both the front and back side of the REB, at level 2.

An interesting finding during this test is that a diameter of 800mm (as described in Chapter 5.2: Ideation and Concept choice) is too large for the EcoModule. With a diameter of 800 mm, the module can only be placed where there is no Reefblock underneath. This resulted in a reduced diameter (600mm) of the EcoModule.

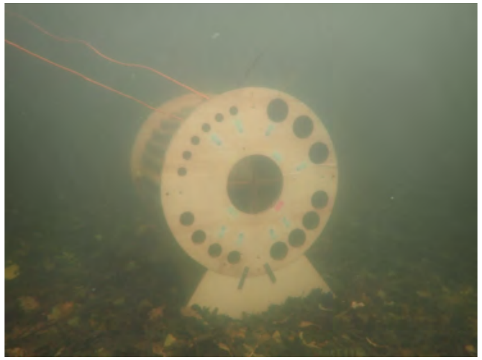
5.4.2 WILD bijzonder vissen

The organisation WILD bijzonder vissen has facilitated its fishpond to test the behaviour and habitat of the eel. A test module (Figure 64) was developed and placed in the mixed pond using ropes (Figure 65).


Figure 64: Test module


Figure 65: Installation

The test habitat was placed on the ground surface at a depth of two and a half meters (Figure 66). The mixed pond was filled, according to WILD bijzonder vissen, with trout, perch, roach and eel. This module examines whether the Eel has a preference for a specific fill material [test1] and different habitat sizes [test 2].



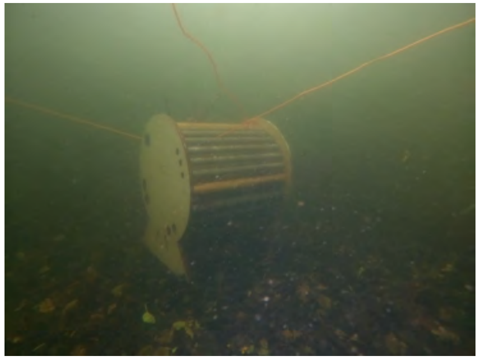


Figure 66: Module a ground surface

Test 1: Fill Material

Compartments (Figure 67) are used to examine whether the Eel chooses a habitat filled with a natural material or chooses an empty habitat. If the Eel chooses a compartment filled with a material, it is examined which material the Eel prefers.

Compartment 1: Empty
Compartment 2: Willow branches and bark
Compartment 3: Seagrass
Compartment 4: Coconut fiber/rope


Figure 67: Compartments (Left: under water, Right: above water)

Coconut rope and willow branches were chosen because these materials are already used in Eel chutes. Coconut fiber was also placed in compartment 4 because, according to research, eels like to wriggle into spaces (klein breteler, 2005). Seagrass, which looks and feels like a fibre, is a plant species that can survive in both fresh and salt water (Jong, 2004) and therefore may be ideal as material for the eel habitat.

Test 2: Habitat sizes

The enclosure of the module is constructed of PVC tubes with different diameters (32mm, 50mm, 70mm and 80mm). The tubes indicated with an arrow are closed on one side, the tubes without an arrow are open on both sides. Investigated is, which tube the Red/silver eel prefers.

The test is done using observation, which are captured with photos and videos. Leon Haines, the Co-founder of Reefy and a certified diver (Figure 68), has experience in underwater observation. Using an advanced camera with red light and a go pro, the habitat is observed for two hours. Stickers were placed on the entrance side in order to easily read which compartment or diameter of a tube is used (Figure X).

Figure 68: Diver, Leon Haines

Figure 69: Stickers

Results

Unfortunately, no Eel were spotted in the mix pond. The diver spent two hours observing in the water and found no Eel in either the habitat or the rest of the pond. A Go pro camera was installed at the module to observe (1 hours) without scaring off the eels, these images also yielded no results of the Eel. However perches were spotted around the habitat.

Figure 70: Go pro installation

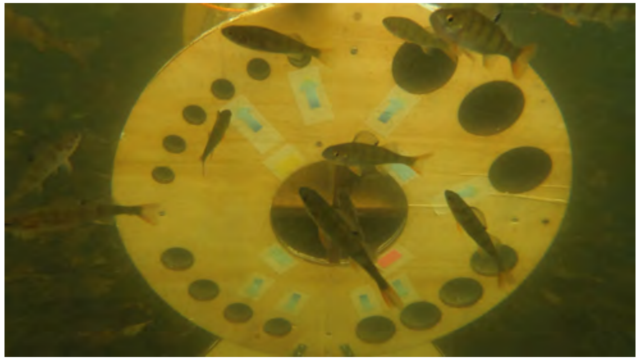


Figure 71: Perches around module

After discussions with the experts from "WILD bijzonder vissen," it is believed that with the cold weather the Eels are no longer moving away from their original habitat.

An alternative test is conducted. The prototype was placed in an eel basin (Figure 72) where the eels are stored before being released into the pond. This test brought very interesting findings.

Figure 72: Eel basin

Soon after placement, eels entered the 50mm, 70mm and 80mm tubes, either individually or multiple at a time in one tube (Figure 73). The eels used both the closed and open tubes. It was also observed that four eels hid in the compartment with coir fiber and rope and one eel hid among the willow branches and tree bark.

Figure 73: Eels hiding in PVC tubes

Even two more eels came out of the coconut rope and fibre after the module was removed from the water. The eels sought shelter, even on land (Figure 74).

Conclusion:
-Eels prefer tubes between 50-80mm in diameter.
-Coir rope and fibre is the material the eel prefers to hide in.
-Habitat draws attention of other fish species

Figure 74: Eel on land

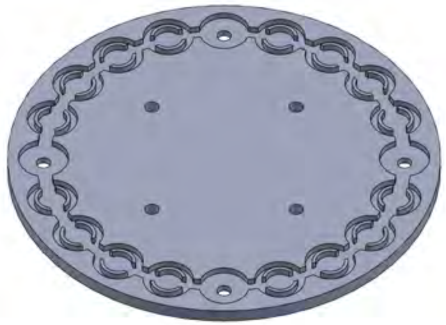
5.5 Detailling of concept choice

The concept choice is detailed with input from the results obtained from the tests and main takeaways from building the prototypes. The detailing phase distinguishes between the housing of the Module, the fastening methods and customisation parts.

Housing 1

Diameter 600mm ; Thickness 20mm
Cutouts 70mm; Bolt holes 20mm

slits added voor customisation parts

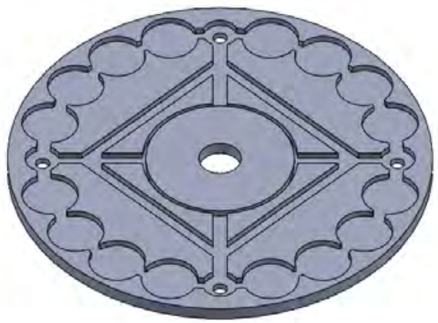


Borders added to differentiate between diameters of tubes

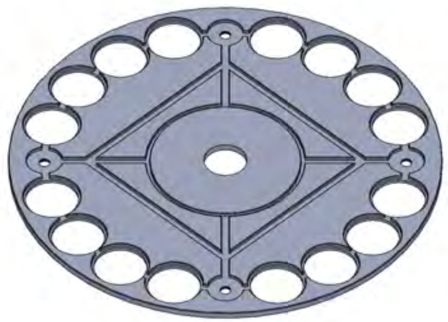
Cutouts for strucural steel tubes reduces to 50mm, Saves cost and weight , creates more space for customisable tubes

Diameter of cutouts increased to 80mm
Removal of border, to complicated

Center hole (60mm) instead of four holes
Change in fastening method



Slits for internal customisable parts



Thickness reduced to 15mm, saves weight and material
Holes for customisation tubes, saves weight, gets enclosed by reefblock
Chamfers added for easy assembly
Size of four fastening holes reduces to M15, thread added

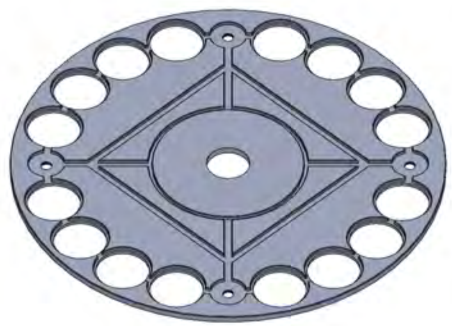
Housing 2

Steel bars
Diameter 50mm
Tapt holes

Steel tube
Tapt holes

Steel thread (one side)
Tapt hole

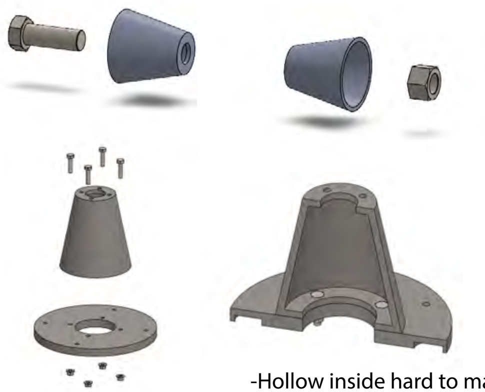
Housing 3



Emerged from housing 1

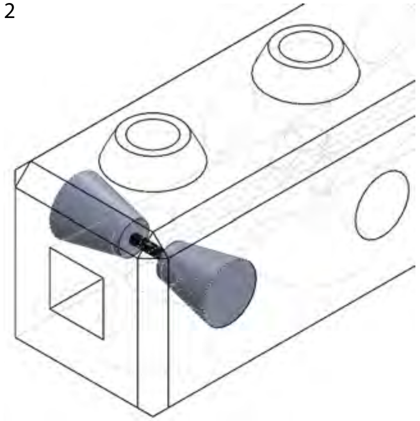
Middle hole functioning as main entrance
M15 thread removed, benificial for tensioning and reduction is thickness (10mm)

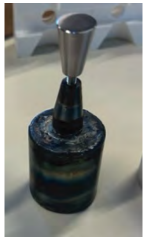
1



-Hollow inside hard to make
-Low strength
-Unnecessary bolts

2

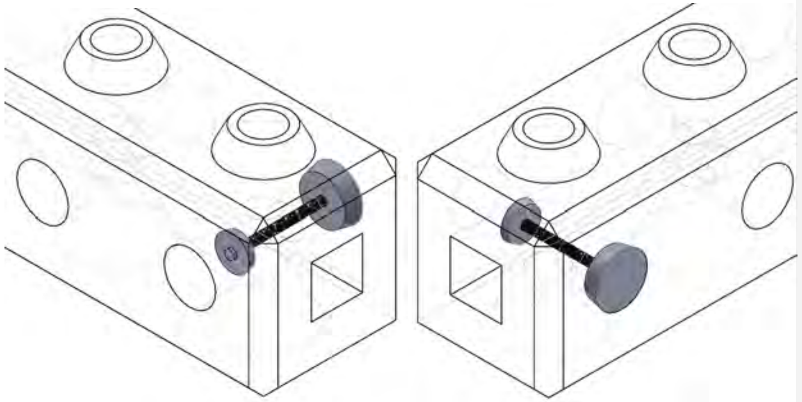




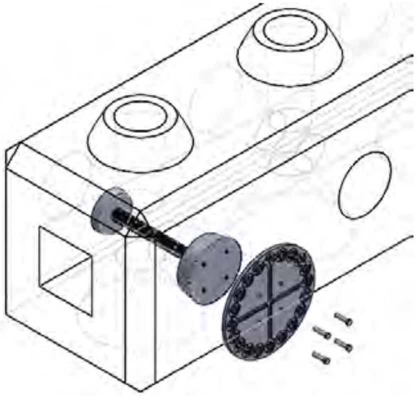
-Emerged from steel prototype
-Solid, allows for tapt holes
- High volume

3

-Reduced in volume --> reduced weight
-Solid, allows for tapt holes
-Nut-shape included to turn and tension fastening method

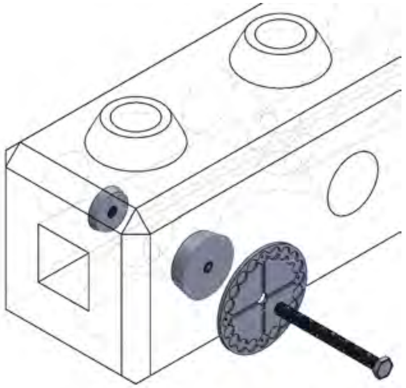


4



-Uses 4 M15 bolts to fasten, low strength
-Multiple parts, increases assembly time

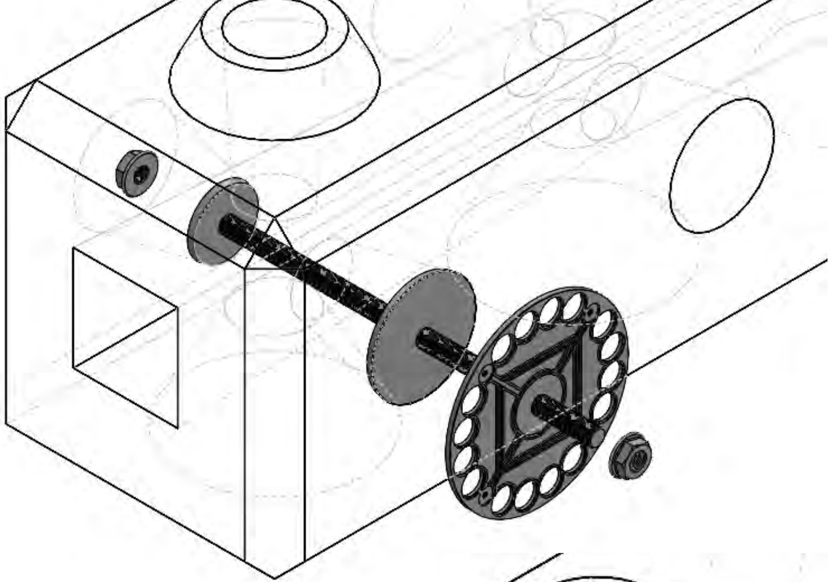
5

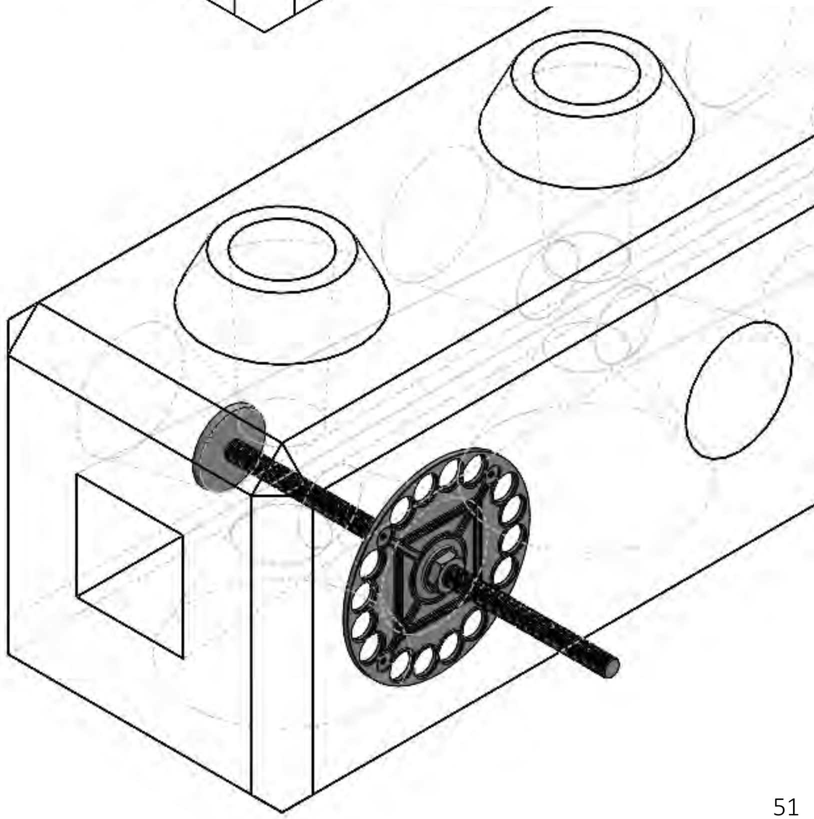


-Combines Housing 1 with fastening method
-Stronger option, easier to assemble, less parts
-Still heavy, small tapered shape (thickness 50mm): 15kg
-Big tapered shape (thinkness 100mm) :64kg
-Uses M48 bolt, no standard part, high cost for development

FINAL

-No thread holes, uses hex flange nuts for tensioning
-Thickness (fastening) reduced from 50/100mm to 20mm
-Weight reduced: Small tapered shape: 15kg -->5kg
Big tapered shape: 65kg -->14kg
-Chosen for M48 threaded rod, standard part
-Increased length: expands opportunities for customisation





Customisation parts

Most of the parts listed below originate from the design process of housing 1. This part provides the slits into which the customisable parts fit.

According to the 'WILD bijzonder vissen' test, the largest size tube, 80mm, is chosen (Figure 75). It has been observed that eels crawl into the tubes alone or with several at a time. Whether the tube is open or closed on one side makes no difference. So the tubes do not need to be open on both sides.

Figure 75: 80 mm tubes

The occupancy of several eels in one tube was so high that this resulted in a main tube with an opening of 150mm. This can accommodate a plaice of eels. This tube also provides entrances to internal compartments filled with coir fiber and rope. To make this possible, holes are made in this tube (Figure 76).

Figure 76: Main tube with holes

The (wooden) panels in the 1:1 prototype worked well, providing additional strength to the habitat. Therefore, these will be included in the final design. More panels (Figure 77) are needed to accomodate multiple habitat area's and to hold the coir fibre/rope. The panels do not cross the main entrance (as in the prototype) but are designed to be placed around the main tube

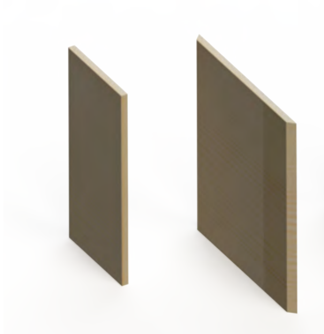


Figure 77: Wooden panels

Assembling the housing of the prototype was doable but difficult. For this reason, a separation component (originated from housing 1, material removed where possible, Figure 78) was designed (as extra) to facilitate assembly while allowing multiple internal spaces to be created. However, this part is not essential for the final design. It is visualised as steel part however this can be made out of any suitable bioreceptive material because the part is not structural. Figure X shows a panel that can be used to completely seal off habitat areas from the outside, again this can be made out of any type of bioreceptive material.

Figure 78: Separation component

Figure 79: Enclosure panel

6. Sustainability

Life cycle assessment

During the design process, various sustainability aspects were taken into account using a Life cycle assessment (Figure 80). This LCA shows the steps that are involved in the product life of the EcoModule. As discussed earlier, after the module is placed in the water, it is not taken out anymore. Recycling is therefore not possible. One of the main aspects therefore is durability.

The resources and processing steps are avoided in the EcoModule Lifecycle. Recycled semi-finished products are used that are easy to manufacture into the desired shape. Only four components are developed specifically for the EcoModule, all other components are purchased as standard and are cut to size. Simple production techniques (Chapter 7.1: Feasibility) are used and is therefore accompanied by low emissions

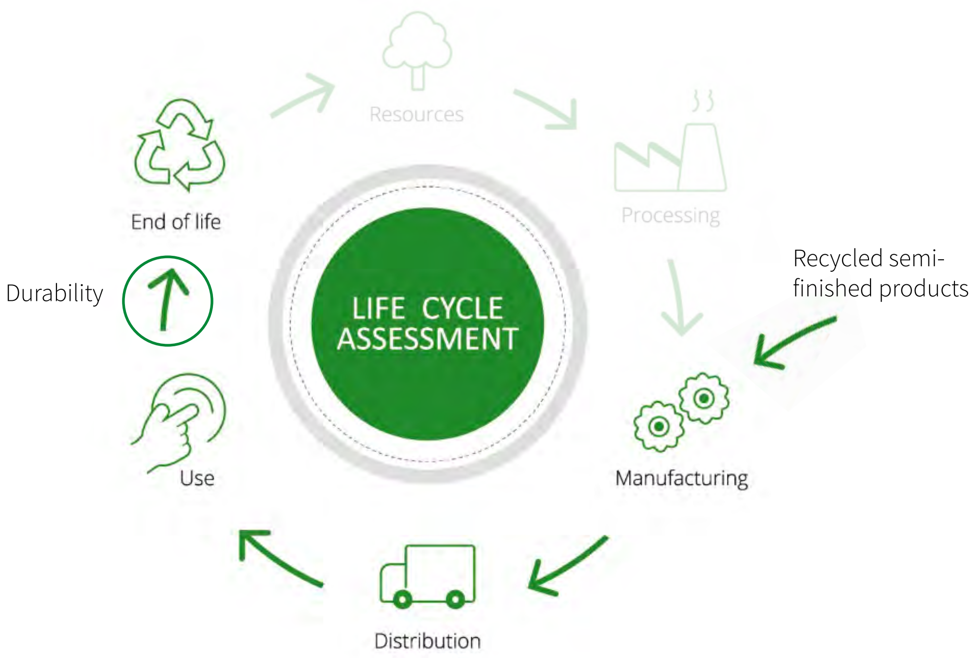


Figure 80: Life cycle assesment EcoModule

Materials

The materials below are non-biodegradable and have a long lifetime, as they act as a habitat structure.

Recycled Q235 steel
Steel is one of the most sustainable construction materials. The overall recycling rate of steel nowadays is 81%. Also, 97% of by-products are recycled (CSSBI, 2023). The EcoModule does not need primary raw materials to be developed for its structural parts. The durability of steel is very high, however, when placed in water, corrosion will occur. According to Yang et al. (2022), the corrosion rate of steel in seawater is 0.192mm/year and according to Ding et al. (2018), 0.13mm/year, this means that when steel is under water for an average of 7 years, only 1mm corrodes, proving it's long lifetime. A study also shows that this is inhibited over time when a biofilm forms on it (Southwell et al., 1974).

PVC
This type of plastic can be fully recycled up to 8 times (VinylPlus, 2023). The material does not require primary raw materials either. PVC can be used in multiple applications and is ideal for waterlogged conditions. According to Folkman (2014), the average lifetime of PVC is 47 years and therefore very durable. Microplastic degradation has also been proven to be negligible (Mintenig et al., 2019).

Populus wood
Wood is chosen because of its low cost, lack of toxicity and good compatibility with marine environments. According to Levy (1987), wood degrades at a high rate when it comes into contact with oxygen, when the wood is in a waterlogged/aquatic environment (which the EcoModule will always be), degradation will proceed at a slower rate and will therefore survive for an extended period of time.

A very important issue is the prevention of ocean waste. It is therefore important that the Module is monitored after installation. If the module is found to be on the verge of breaking down, it will have to be removed from the water, which can be done by grinding off one rusted flange hex nut. The materials will still recyclable.

When looking at the full context, the EcoModule will contribute to building ecosystems and boost biodiversity. The REB together with the EcoModule therefore contribute to environmental sustainability.

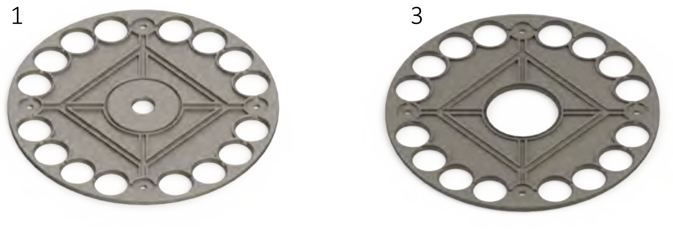
7. Assessment

7.1 Feasibility

Structural parts

To be developed

Housing 1 & 3



Method: CNC milling (Figure 81) .Dxf files required (Appendix 13)

It is possible to mill the housing in one go. However, the first time it is necessary to program how the CNC machine should work. This requires high labour costs, but is only needed once (personal communication, employee PMB industrial design engineering).

Figure 81: CNC-machining

One 600x600x15mm (housing 1) and one 600x600x10mm (housing 3) plain carbon steel plates, must be pre-cut (laser/plasma/water) to minimise material loss and no need of very large cnc machines. This machine could cut all the holes going all the way through the steel plate, this saves costs on CNC milling

Housing 2

Method: Cutting/welding

-Extruded low carbon steel tube (50x590mm, wall thickness 3mm, Figure 82)
-Welding socket male (47x30mm, Figure 83)
-Welding socket female (47x30mm Figure 84)

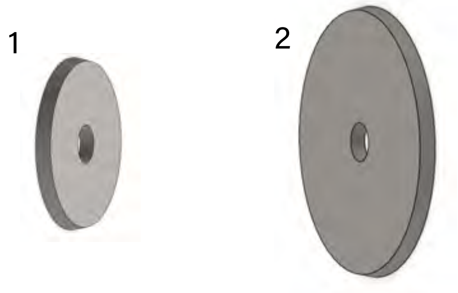
Figure 82:
Low carbon steel tube

Figure 83:
Welding socket male

Figure 84:
Welding socket female

-Steel tube cut to desired length using a metal cut-off saw
-Welding sockets welded to steel tube

Fastening part 1 & 2

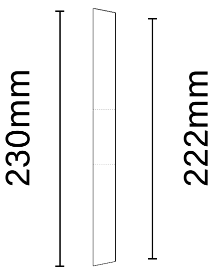


Method: CNC-turning (Figure 85)

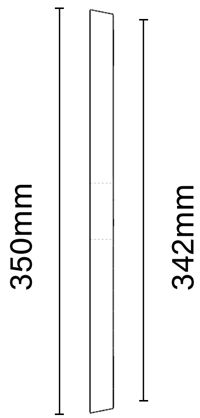
Disc including centre hollow is cut from plate (laser/plasma/water). Disc is tensioned onto CNC turning machine from the inside. This way, no additional material is needed to hold the part to be turned.

Figure 85: CNC turning

Fastening part 1
11.3 degrees
230mm/222 mm
Center hole 48mm



Fastening part 2
11.3 degrees
350mm/342 mm
Center hole 48mm



Standard parts

Threaded rod 48x1300mm, cut to desired length using a metal cut-off saw

Flange hex nuts M48

Flange hex bolt M15

Non-structural/customisation parts

Main tube
extruded PVC tube 150mmx600mm,
cut to desired length using a bandsaw or
cut-off saw. Create holes using drilling.

Tubes
extruded PVC tubes 80mmx600mm,
cut to desired length using a bandsaw
or cut-off saw

Panels [a]
(populus) Wooden panels 150x600mm,
cut to desired length using bandsaw
or table saw

Panels [b]
(populus) Wooden panels 200x600mm,
cut to desired length using bandsaw or table saw.
Cut 45-degree sides using a table saw

7.2 Desirability

In a project like this, it is difficult to prove desirability. A desirable product addresses the user's values and needs. In this project, the European eel is the end user and other marine organisms are users too. Normally you can receive verbal confirmation from users, however, in this case that is not possible.

Therefore, to demonstrate desirability, literature was used. The literature proved that different bioreceptive materials fulfil the needs of various consumer, producer and grazer organisms. Bioreceptive materials have been used in the EcoModule which are mainly colonised by benthic communities, food of the eel, a need of the end user.

This thesis also investigated what kind of habitat the eel feels comfortable in. Using literature, a habitat was developed and then tested in TRL 5, with eels. This test showed that eels use/hide/rest in PVC pipes, preferring a diameter of 80mm. Eels also seek shelter which was proven with the test model, the eels prefer to hide in coir fibre and rope.

7.3 Viability

To prove the viability of a product, it has to meet several aspects. You can ask the question: should you bring the product to the market? A viable product must provide value for business, customers and society.

Business
Will investment costs translate into sales and profits? Important here is the cost price and the selling price.

The cost price for a single EcoModule is €497 (excl VAT) (See Appendix 14 for the calculation).
Material, machining, labour and assembly costs have been taken into account. This price gives a good indication of the cost price, but can only be determined exactly when the EcoModule goes into production. This is because the price is calculated on the basis of material costs/kg. During the manufacturing process you have to deal with material loss, which can lead to a slightly higher production cost.

On top of this price there are transport and investment costs. The transport costs depend on the location where the REB will be placed, which is not yet clear and therefore not included in the cost price. A one-off investment of approximately 550 is required to programme the CNC milling (500) and CNC turning (50) machines to the desired settings. Should the EcoModule be mass-produced in the future, steel casting may be a consideration (see Chapter 10: Recommendations).

The average selling price (depending on location) of the Reefblock is between 450-600eu/m3 (incl VAT). Were you to sell the EcoModule at the same price, a profit margin of 60% would be achieved (excluding transport and one-off investment). But before people are willing to buy the EcoModule, as an addition to the REB, the product's performance has to be proven.

Customer
This aspect requires zooming out and looking at the whole picture. To convince buyers, it will have to be proven that the EcoModule works in combination with the REB, The EcoModule will have to be placed in a REB in the sea and monitored over a time period of at least a year. The monitoring can provide images that can convince investors and potential buyers on how the REB works with an ecological enhancement.

Although the product has not been tested at TRL 7 (operational environment), enthusiasm about having an ecological enhancement is high. The organisations Rijkswaterstaat, Boskalis and the municipality of Rotterdam are very interested in installing the nature-friendly Reefblocks in combination with a boosting EcoModule. This has been proven because the Reefy system was chosen at the time (October 2022) for a pilot project in Rotterdam, the then-named EcoBlock was pitched and helped ensure that Reefy was chosen because of its dual function, the 'environmental breakwater' (personal communication, Leon Haines; Blake, 2022).

Recently, Reefy's co-founders visited resorts in Mexico. This showed that interest in the REB with ecological enhancement is also high. The combination is interesting for resort owners because it not only protects their coast but also creates a diving spot that is appealing to resort customers. The EcoModule can boost biodiversity in and around the REB but could also attract specific, rare marine species. The EcoModule is currently designed for eels, however, a rare species of interest to divers could be designed in the future using this thesis and the customisable EcoModule.

Society
Installing the Reef Enhancing Breakwater with the EcoModules prevents coastal flooding and boosts biodiversity by providing habitat, bringing a positive gain to society and marine society.

8. Conclusion

A bioreceptive ecological enhancement that boosts a marine infrastructure called, Reef Enhancing Breakwater (REB) created by the startup Reefy, has been developed. This thesis showed how to do a study on attracting and providing habitat to a specific macro marine species, in this thesis the European Eel. The concept, The EcoModule, offers customisability meaning that the product can easily be adapted to the needs of an alternative marine organism. This can be done through differentiation of materials or by rearranging the customisable parts in the design.

The concept derives its strength from simplicity, low cost and customisability. Three durable materials were used in the development of the EcoModule: Recycled Q235 low carbon steel, Polyvinyl chloride (PVC) and Populus wood. These materials have bioreceptive properties that mainly attract benthic communities which serve as food for the eel. The concept consists of tubes that act as enclosures of the module and provide internal habitat space. A strong steel structure is designed to fit the tapered side holes of the Reefblock, allowing the EcoModule to be attached to the REB.

Tests have shown that the module does not negatively affect the operation of the REB, that eels individually or collectively use 80mm diameter PVC pipes and that the module will be filled with coir fibre and rope in suitable habitat areas enclosed by populus wooden panels.

The EcoModule is complementary to the Reef Enhancing Breakwater as it ensures the attraction of macro organisms that keep an ecosystem running. Currently, a proof of concept has been developed for the European eel, in the future this thesis can be used as a guideline for the development of a product targeting alternative organisms, the EcoModule can be used as a basis and can be adapted to the needs of a specific species.

9. Discussion

A proof of concept has been designed which, supported by literature and various tests, proves that the EcoModule can act as a habitat for macro organisms, in this case for the European Eel. However, the marine world is very difficult to predict.

To actually prove this product, the EcoModule will have to be installed in the sea, the REB and module will have to be monitored over a period of one to two years. This is necessary to see whether an ecosystem will run on the REB but also whether eels will use the module in this context. There is a possibility that the module will not be used at all or be used by other organisms.

An initial concept of Reefy, The Ecoblock, was placed in the river Maas near Rotterdam in October 2022 to test the above. At the time, the block was filled with natural materials with no substantiated study. The Ecoblock had already broken down within 4 months and caused pollution. It is therefore important that the construction of the EcoModule is firm and will last for years. The construction and fastening method was designed from my own experience of material constructions with the assumption that it will not break down. To prove this, the Module will have to be placed in the sea, this is the best way to monitor whether the construction is firm enough. A second option would be to develop a 1:20 or 1:15 model, with appropriate scaling laws, and test it in the wave simulator at Deltares.

The most common reaction to the developed construction from stakeholders was that it might be too strong/robust. In this thesis, this has been substantiated with rather too strong and a bit more expensive than an EcoModule that ends up as waste in the sea. Material and costs could be saved in areas in the design that have been proven, by calculation, to be unnecessary.

Finally, the use of PVC is a point of discussion. Despite PVC being proven to have a very long lifespan and little to no degradation of microplastics, people are skeptical about plastic in the sea. When selling the product, this can become an issue. Therefore, alternative materials, such as the biopolymer Arboblend, have been investigated. However, little is known about this material so more research will have to be done here on whether it is suitable as a material for the EcoModule. More materials are discussed in Chapter 10: Recommendations.

10. Recommendations

Before bringing this concept to the market some recommendations are given on steps to be taken after this thesis.

Conduct a test and monitor in an operational environment (TRL 7)
This will prove whether the Reefblock and EcoModule are colonised and whether the added habitat is used. The monitoring will provide results and visualisations that can be used to convince investors and/or potential buyers.

Reconsider using PVC as material
I would recommend using PVC because eels prefer to rest or hide in these tubes, the material is proven to be bioreceptive, has high durability and no degradation of micro plastics. Is it noted that people are skeptical about plastic in water, then the biopolymer Arboblend could be a substitute. However, more research is needed on this material in the areas of bioreceptivity, durability and cost.

Alternative suitable materials are: Basalt, Gabbro, Terra-cotta, Solanyl and Limestone (created from dissolved minerals using electrified steel)

Tests and calculations on EcoModule structure
Three ways can be used to test whether the EcoModule is wave energy resistant: Test in TRL 7 [1], Test, according to proper scaling laws. 1:15 or 1:20 scale models in wave simulator [2] or find an expert in this area who can perform calculations on it [3]. These findings or calculations can prove if the module will survive and whether material can be removed to save weight and costs. Mainly focus on the fastening part (1&2) and the threaded rod. It is recommended to look at a threaded tube instead of a threaded rod (weight reduction: 12kg to 2.5kg), because the forces on this part are low

Take into account the expansion coefficients of the materials
The North Sea varies in temperature between 3 and 20 degrees. The temperature difference of 17 causes change in length of the materials. The following margins must be taken into account when developing the EcoModule (calculations, Appendix 15):

Carbon steel: 0.1224 mm
PVC: 0.816 mm
Populus wood: 0.0816 mm

Study on supply chain and transport
This thesis has shown the ideal mode of transport for a fully assembled EcoModule (Figure 86), which helps with on-site installation. When the EcoModules are transported over a very long distance, the fastening method can be considered as individual parts (Figure 87). Research will have to be done on the ideal supply chain and associated costs.


Figure 86: Fully asembled EcoModule


Figure 87: Fastening parts as indivduals

Study on steel casting
CNC milling and turning are ideal manufacturing techniques to produce the housing and fastening parts. Should the EcoModule go into mass production, developing a mould and casting steel is an option. This brings high investment costs but a lower production cost in the long run.

Add textures
During the research, it often emerged that the use of textures is beneficial for the colonisation of micro-organisms. Textures can easily be applied to both housing 3 and the wooden panels.

Possible alternatives for tubes


Figure 88: Perforated steel

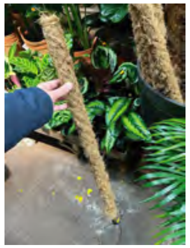


Figure 89: Coir tube


Figure 90: Braided wood

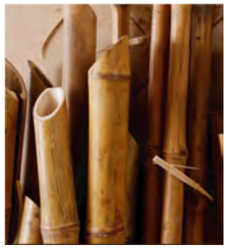


Figure 91: Bamboo

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13. Appendix

Appendix 1

reefy
innovation for nature

Date 2023.03.28
Place Delft

Subject: Graduation thesis assignment Product Design –
Design of Cubic Ecological Enhancement for Marine Infrastructure

Reefy is an innovative startup in Delft that combines coastal engineering and marine biology to create nature-inclusive marine infrastructure. Currently we are developing a modular artificial reef with a breakwater function. This year, we managed to successfully produce and install 17 of these ReefBlocks in the water during our first large-scale pilot. Added to this underwater structure were cubic ecological enhancements, called EcoBlocks. Presently, we are looking for a highly motivated and proactive student to help with the next iteration of these EcoBlocks.

We are seeking a Master's student to join our team, while working on their thesis project. During your graduation, you will work on the following exciting research objectives.

1. Design, 3D model and prototype of an attachment system based on the inner tubular system of the ReefBlock, that allows for interchangeable components to be fastened.

2. Design, 3D model and prototype of a cubic outer frame functioning as housing to interchangeable eco-friendly inner components that connect to the attachment system.

3. Designs, 3D models and prototypes of multiple internal subassemblies providing suitable hiding-, resting- and/or reproduction enclosures for diverse local marine organisms.

4. Proposal of material selection, assembly- and production instructions for the above-mentioned parts substantiated by their context impact characteristics (salt water resistant, stability in wave conditions), mechanical properties and environmental impact.

Our goal is to optimize our current EcoBlock designs based on durability, feasibility, sustainability and viability. This research will contribute to the development of nature-inclusive and resilient infrastructure projects of the future by working together with nature.

The assignment requires a design student who is highly proficient in 3D modeling (preferably in SolidWorks), advanced prototyping, able to work independently, and who possesses a great deal of motivation and sustainable mindset. If you are interested, please reach out to info@reefy.nl with your CV, motivation letter and portfolio.

1|Reefy

Appendix 2

6682

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: den Hollander
initials: D.P.O. given name: Daan
student number:
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): [x] IPD [ ] Dfl [ ] SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: [ ] Honours Programme Master
specialisation / annotation: [ ] Medisign
[ ] Tech. in Sustainable Design
[ ] Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Erik Thomassen dept. / section: SDE / MF
** mentor: Ward Groutars dept. / section: SDE / MF
2nd mentor: Leon Haines
organisation: Reefy
city: Delft country: The Netherlands

comments (optional): Chair and mentor from same section but with totally different expertise area's.
Ward: Bioreceptivity
Erik: Structural engineering

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

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

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Erik Thomassen date 11 - 07 - 2023 signature [signature]

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 27 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 27 EC

List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed

NO missing 1st year master courses are:

name Robin den Braber date 24 - 07 - 2023 signature RdB

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: V APPROVED / NOT APPROVED

Procedure: V APPROVED / NOT APPROVED

Despite a new rule, the chair is allowed to supervise this project once as a chair without a PhD mentor

comments

name Monique von Morgen date KE 22/8/2023 signature MvM

Design of Bioreceptive Ecological Enhancement for Marine Infrastructure project title

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

start date 11 - 07 - 2023 | 08 - 12 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

This project is in collaboration with the startup called Reefy.

Reefy combines coastal engineering and marine biology to create nature-inclusive marine infrastructure. Reefy has successfully developed the first modular artificial reef capable of dispersing wave energy to safeguard the coast while simultaneously offering the necessary foundation and habitat structures to enhance marine biodiversity. This is achieved through the implementation of bioreceptive "Reefblocks," which are 3 by 1 meter concrete blocks with an inner tubular system (Figure 1).

Coral reef covers only 0.01% of the seabed, however, it supports 25% of marine life and 97% for dissipating wave energy before it reaches the shoreline.

The company Reefy wants to create a habitat for various organism by placing concrete blocks which at the same time prevent flooding. Reefy has succeeded in growing a coral reef on both biodegradable biopolymers and low-emission cement-free geopolymer concrete.

An opportunity is to use the Reefblocks to increase the amount of reef organisms, create a habitat and thereby protect the land. However, to ensure that reef organisms will grow on these Reefblocks, algae formation should be prevented and biodiversity will need to be stimulated. An initial idea, the EcoBlock (Figure 2), should provide a solution to this. Some initial steps have been taken to design this block, however there is no proof of concept or working prototype yet.

space available for images / figures on next page

introduction (continued): space for images

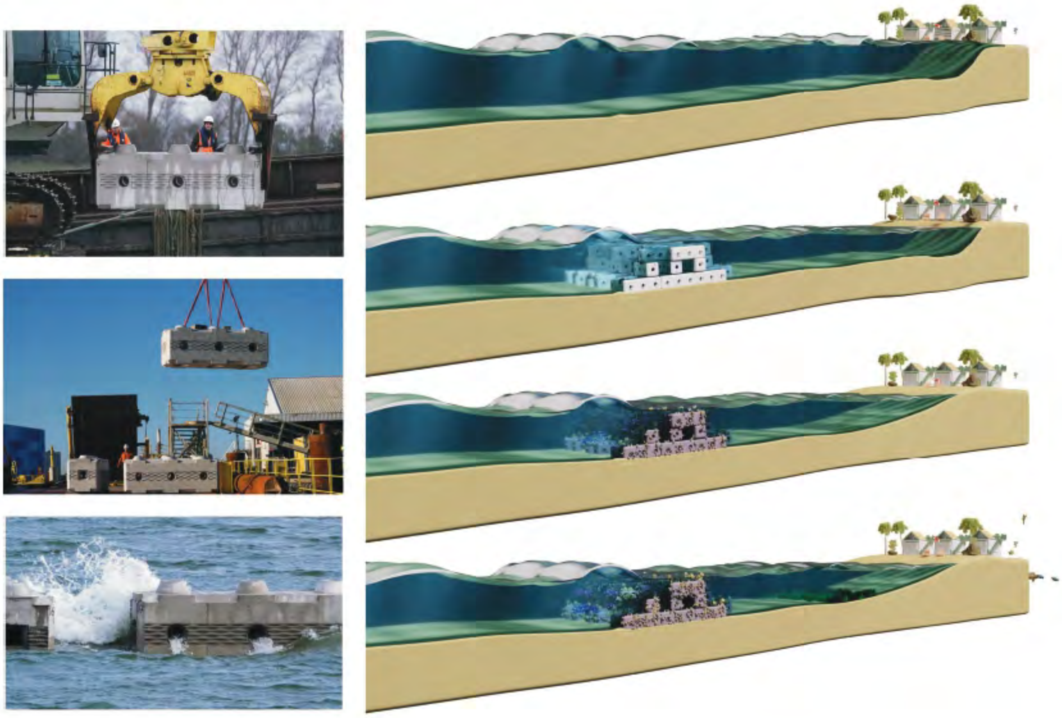


image / figure 1: Reefblocks operation

image / figure 2: EcoBlock

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Creating a habitat for local marine organisms is what the Reefblocks are supposed to do. The material used in the Reefblocks makes this possible, however the attraction of local marine organisms is not yet successful. The Reefblocks provide limited space that serves as hiding places, an enhancement to the current configuration can provide a habitat for organisms uncomfortable with living in the Reefblocks or attract organisms that will live in them. Also, macroalgea can grow on the Reefblocks, making it harder for reef organisms to grow on it.

Various, location-dependent organisms should be attracted to live in and around the Reefblocks, enhancing biodiversity and preventing algal saturation. This also allows the installation of the Reefblocks to comply with policies that are applicable in this context.

The concept, the Ecoblock should provide a solution for this. The Ecoblock is an add-on to the current Reefblock structure to attract local marine organisms. What this block will look like geometrically, how it will attract organisms and how it will be attached has not yet been examined. A Minimal Viable Product is currently being monitored of which no results are yet available.

The initial idea of the Ecoblock needs to undergo a revision process from start to end based on durability, feasibility, sustainability and viability. Starting with researching the ecosystem and how to attract local marine organisms, which will lead to a design that can be integrated or attached to the current Reefblock structure.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The aim is to design a (modular) product which enhances the bioreceptivity of the Reefblocks configuration by attracting local marine organisms, depending on the location.

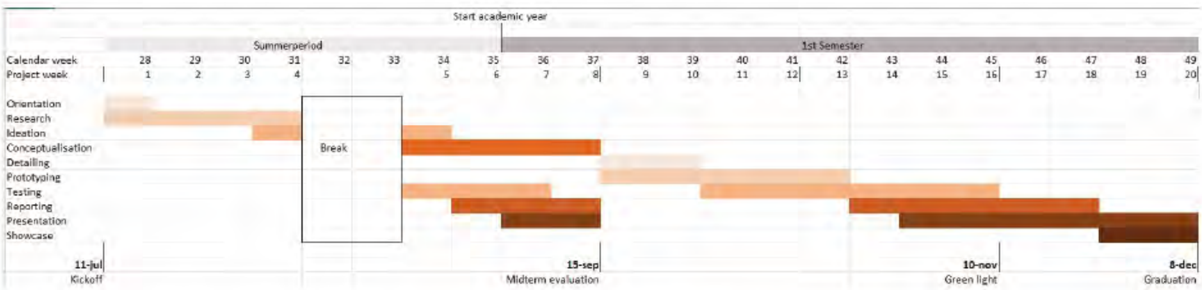
Subquestions:
1. Research on current, location dependent, reef ecosystems.
2. Research and proposal of materials on how to attract specific local marine organisms, which could prevent algae saturation and comply with policy standards.
3. Design, 3D model and prototype of an integrated/attachment system based on the inner tubular system of the ReefBlock, that allows for interchangeable components to be fastened.
3. Design, 3D model and prototype of an outer frame functioning as housing to interchangeable eco-friendly inner components.
4. Design, 3D model and prototype of multiple internal subassemblies providing suitable hiding-, resting- and/or reproduction enclosures for diverse local marine organisms.
5. Proposal of material selection, assembly- and production instructions for the parts substantiated by their context impact characteristics (salt water resistant, stability in wave conditions), mechanical properties and environmental impact.

The objective is to provide a product, along with a strategy for manufacturing a bioreceptive enhancement as well as attracting targeted local marine organisms.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and 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 activities.

start date 11 - 7 - 2023 | 8 - 12 - 2023 end date



My approach to the graduation project is to work on this full-time, with a two week holiday.

The dates for the evaluation moments are listed in the Gantt chart and are definite. Should there be an overrun, I will communicate this in time and set a new date in consultation.

I would like to have a meeting (at TU Delft) with the supervisory team every two weeks to discuss the progress. If possible, besides the standard meetings, I would like to have the option of speaking to members of the supervisory team more often, remotely.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I see myself as a product designer. I have always enjoyed turning an idea into something tangible. My passion lies in coming up with an idea, modelling, prototyping, testing and validating. During both my Bachelor and Master, a finished concept was often the end of the project. The Advanced Embodiment Design course was decisive for me in that I see myself as a product designer who likes to take a concept to a higher level. I saw these aspects reflected in the Project Brief provided by the company Reefy. My ultimate goal is therefore to realise a working protoype, which can actually be tested in the water. Besides feasibility, durability and viability, I think sustainability plays a big role in this project. This is also one of the things that attracted me very much because I think that any product in the future should take this into account in a design process.

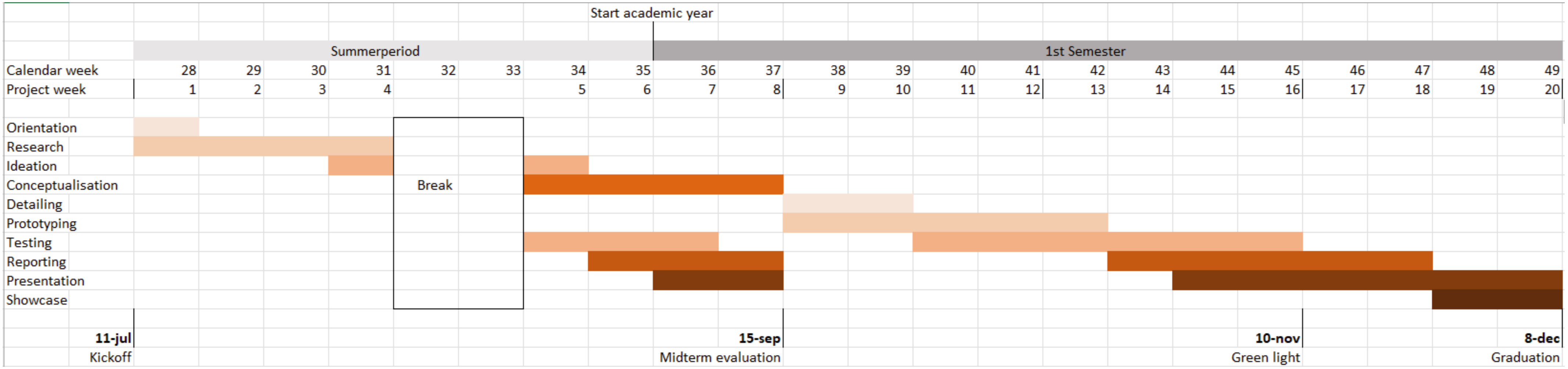
Very interesting to me about the company Reefy is that their product stands for multiple purposes. As discussed in this project brief, it is about coastal protection and at the same time creating a habitat for organisms. Protecting the land by using nature.

The first thing I would like to learn during my graduation project is to work with a company. I think that besides the supervisory team, I can learn a lot from the experts within the company. I also see an opportunity to learn a lot about bioreceptivity, manufacturing processes and integration/installation methods. I think it will be quite a task to design a product that can withstand the forces of the sea. Finally, I think I will learn a lot about a managing position within this project, it will be up to me to make this project run as smoothly as possible. All stakeholders within this project will need to feel involved and know what has happened and what is to come.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix 3

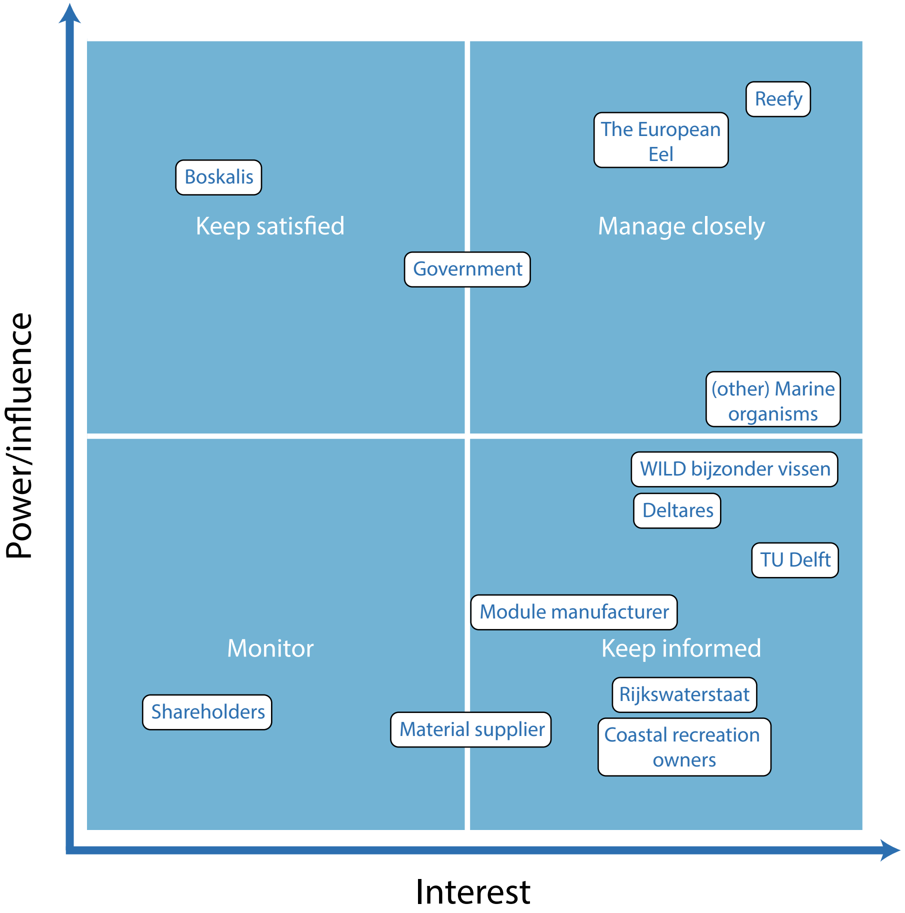

Start academic year
Summerperiod
1st Semester
Calendar week
28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49
Project week
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Orientation
Research
Ideation
Conceptualisation
Detailing
Prototyping
Testing
Reporting
Presentation
Showcase
Break
11-jul
Kickoff
15-sep
Midterm evaluation
10-nov
Green light
8-dec
Graduation

Appendix 4

This chapter presents stakeholders who have influenced the habitat design for the European eel, The EcoModule. A market analysis was done to determine Reefy's competitive position. This analysis helped make choices in the design process.

Stakeholders

Different stakeholders who have influence and/or interest in this project are shown in the Figure, which are discussed in the Table.



Direct stakeholders	
Reefy	Reefy is the client and therefore has a high power. The startup facilitates expertise and budget that help develop the EcoModule and therefore influences choices made in the design process. The interest is to become the market leader of coastal protection and facilitating habitat to boost marine biodiversity
TU Delft	TU Delft supports this project with expertise and (prototyping) facilities and therefore has a very high interest but lower power because they cannot make decisions within this project.
The Eel (non-human stakeholder)	The Eel is the main consumer of the EcoModule. For this reason, the Eel has high power and interest. The Eel determines how the habitat is created.
(other) Marine organisms (non-human stakeholders)	Other marine organisms influence the choice of bioreceptive materials used in the EcoModule. Interest is high because these organisms can also use the Module despite it not being designed to their requirements and wishes.
Deltares	Deltares is an organisation that works on innovative solutions in the field of soil and water and therefore has a high interest. The power is medium because the organisation determines how the product can be tested but has no influence on the outcome of the project
WILD bijzonder Vissen	This recreational fishpond has a high interest in this project, because they also support protecting the eel and provide habitat for their species. The power they have is medium, they determine how the Ecomodule can be tested but besides this they have no influence on the outcomes of the project
Boskalis	Boskalis determines how the Reefblocks are installed. The installation method limits the places where the EcoModule can be installed.This maritime service provider therefore has a lot of power but apart from a successful installation has no interest in the outcome of the project
In-direct stakeholders	
(Local) Government	The government has high influence because they can determine what is and is not allowed regarding government and environmental rules. Interest is medium because Reefy's solution ensures coastal protection which makes them a potential customer
Coastal recreation owners (Resorts, scuba diving schools, boat renters)	The power of coastal recreation owners is low because they have no influence on the project. Interest is high because the REB will protect their coast and the number of customers could increase because a scuba diving attraction, with the help of the EcoModule, could be created
Module manufacturer	The module manufacturer has some influence on the embodiment, because of the possible production techniques. The interest is high because if the product were successful the demand would increase.
Material supplier	The material supplier has no power because switching to another supplier is easy (provided it is made of a common material). Should it be a niche material, the power increases a lot. The same goes for interest. The demand for the material can increase when the module is successful.
Rijkswaterstaat (Customer)	Rijkswaterstaat trusts in Reefy. This is a potential buyer of Reefy's product and therefore has a high interest as it concerns coastal protection of the Netherlands. Power is low because Rijkswaterstaat has no influence on choices in the design process

SWOT analysis

To evaluate Reefy's competitive position, a SWOT analysis is conducted (Table).This analysis helps in understanding the market, future opportunities, limitations and sharpening the scope.

The main takeaways from this analysis show that the EcoModule should provide an expansion of habitat space, attract macro organisms, be easy to install, have a low CO2 footprint and all that with low investment costs. These takeaways were translated into requirements and incorporated into the design of the EcoModule (Chapter 5: The EcoModule)

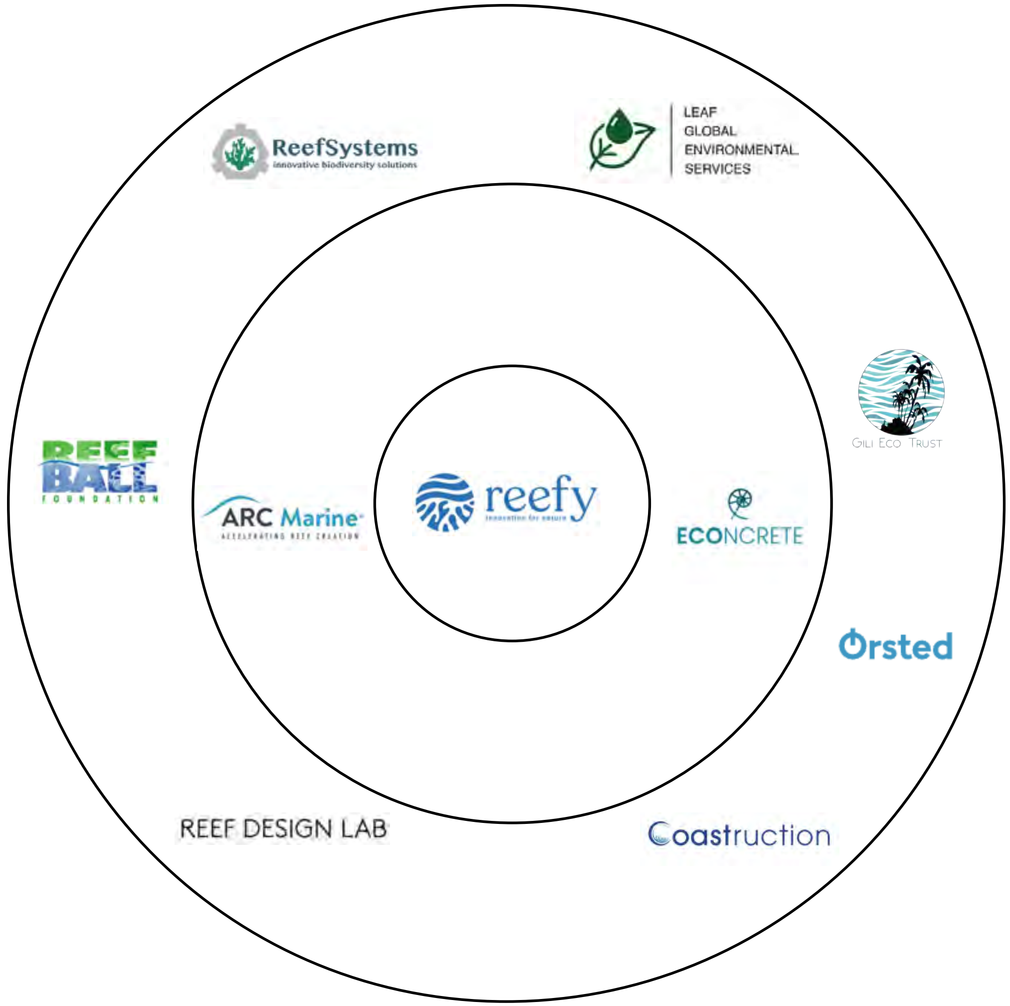
If successfully validated, the EcoModule will greatly improve Reefy's competitive position in the market. Reefy will be the only one in the market that has added an ecological enhancement to coastal protection blocks to boost marine biodiversity.

Strengths	Weaknesses
Combination of coastal protection and artificial reef Attraction of microorganisms Dissipation of wave energy Production costs Low CO2 footprint Patented REB Experience in reef restoration, coastal engineering, water management and ecology Pilot/proof of concept Bioreceptive material usage	Limited habitat space in inner tubular system Attraction of macro organisms (grazers and predators) EcoBlock Limited financial resources Lack of brand awareness Common material usage Macro algae interrupt ecosystems
Opportunities	**Threats**
Save the Eel Restore/boost coral/oyster/mussel reefs Boosts marine biodiversity Expanding the habitat area Create habitat for grazer and predator organisms Create recreation facility	Country specific legal considerations Climate change effects on existing biology Emerging competitors Marine policies that restrict placement of innovative materials Competitors with lower costs Detachment of Reefblocks resulting in ocean waste

Competitor analysis

Reefy's competitors were analysed to gain more knowledge, understand the context and establish a design focus. Many companies make artificial reefs, but few competitors combine this with coastal protection. Two companies, Econcrete and Arcmarine, are Reefy's biggest competitors. These companies also make concrete blocks that serve as coastal protection and marine habitat. The inner tubular system and the way the blocks fit together makes Reefy unique. An addition to coastal protection blocks to boost marine biodiversity and create additional habitat is something no competitor does. Reefy, as mentioned earlier in the SWOT analysis section, can be the first in the market with a patented ecological enhancement, this unique selling point will make Reefy stand out from its competitors.

More companies make artificial reefs, however these do not function as coastal protection. Analysing these competitors helped in researching different types of (bioreceptive) materials, which can help substantiate and validate the material choice. A list of suitable materials is discussed in section 4.1.3 Materials. The choice of material is important to make trade-offs in the design process and it determines the embodiment of the product.



Appendix 5

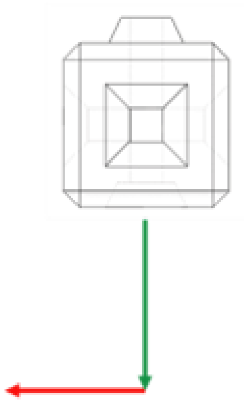
List of Requirements

The product shall
offer habitat to the European Eel
be customisable to the needs of a specific organism
be made out of a bioreceptive materials
not be biodegradable
give the opportunity to use multiple materials
have a low resistance to wave energy
have a durability of at least 20 years
be kept in waterlogged environment until end of life
get its stability from the REB
not have a negative influence on the stability of the REB
not function as a coastal protector
be fastened to a Reefblock on land
weigh a maximum of 100 kg
have a maximum production cost of 600 euros
have a standard volume of 600x600mm
be scalable up to 800mm in length
be attached to one of the side tapered holes of the Reefblock
not depend on the configuration of the REB for placement
consist of one standard housing, made of Q235 low carbon steel
be fastened to the Reefblock using a threaded rod and flange hex nuts
be delivered fully assembled on site
use 80mm diameter PVC tubes and populus wood panels as customisation parts
use coir fiber and rope as fill material

Appendix 6

Challenges

Several challenges occurred during the ideation phase, these challenges were translated into requirements and thus boundaries, which helped with choices in the design process. The occured challenges are listed and discussed below



To place the Reefblocks, hydraulic stones are placed on the bottom of the reef, these stones serve as the substrate for the REB. Using a crane on a boat, the blocks are picked up on the short sides and placed in the water. Placement of the blocks in the water is done using software technology that can determine the exact location for depositing the block. The reefblock is installed vertically (across the y-axis) and placed in the correct location. The Reefblock will never lie exactly straight because of the rough surface. What is avoided during installation is to bring the block down vertically, and move it just above the bottom over the x-axis as shown in the figure above. This operation is not necessary for the installation of the reef block configuration and may disturb the water building blocks on seabed. This installation technique provided the following challenges.

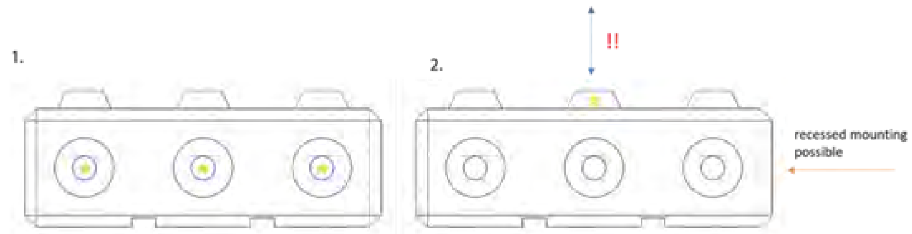
Fastening method EcoModule to Reefblock

Attaching the EcoModule to the Reefblock is a big challenge. In the ideation phase, several options were conceived and consulted. Fastening can be done by clamping, tensioning, clicking or drilling. Clamping the module between two Reefblocks is not possible due to the aforementioned installation technique and the non-straightness of blocks. The EcoModule must therefore be fixed on land and installed as a whole (together with a reefblock).

Placement of EcoModule on Reefblock

Attaching the EcoModule to the Reefblock on land presents the following challenge.

The method of gripping the Reefblock, by the crane, limits mounting spots. The only possible mounting spots for the module are shown in the Figure below. Should the module be placed on top, it is important that the module is not too high so that the crane can still lift the Reefblock.



Location of EcoModule in the REB

The location of the EcoModule in the REB is also important, the module does not dissipate sea currents so will ideally be placed in the lee of the Reefblock configuration. This reduces the chances of the module breaking. It is important to determine in advance where the EcoModule will be attached and where this Reefblock will be placed in the REB.

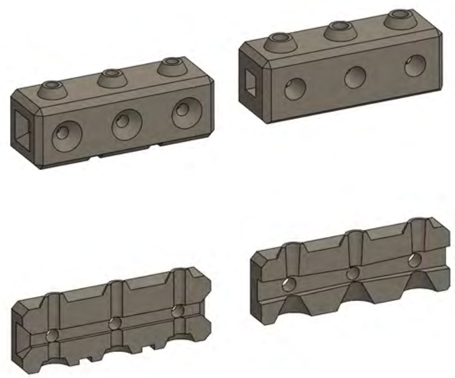
For a long time, the Reefblock configuration was not clear, which made it difficult to find a suitable location for the module. During the design process, the figure below was chosen as the REB.

However, later in the process, the above configuration changed again. Therefore, it was chosen to develop a module that does not depend on the configuration of the Reefblocks. The EcoModule has to fit in several places in the configuration, this means that a good consideration has to be made in the geometry of the EcoModule.

Cost
Reefy is a start-up which means there is not much budget for developing the module. The product should therefore be producible with low investment costs.

Inner tubular system
The inner tubular system is designed to prevent the Reefblock from lifting or tilting. This inner tubular system also provides habitat for marine organisms. You want to take up as little space of this system as possible when attaching the module to the Reefblock. Attaching the EcoModule to the reefblock makes maximum use of one inner tube, this is set up as a requirement.

Adjusted geometry of Reefblock
During my ideation phase, modifications were made to the Reefblock. For me, this meant rethinking attachment methods. However, the modification (tapered inner tube system) to the Reefblock has been beneficial for the chosen fixing method. The figure below shows both blocks side by side including the cross-section (left old block, right new block) The modification allowed for tensioning between two tapered shapes.



Withstand ocean forces
Both the module and the fastening must be able to withstand sea currents.
The material and the fastening method are important.

Therefore, a steel housing was chosen. A steel casing ensures high durability and offers the possibility of being colonized by organisms.

Degradation
The choice of material is important, you don't want the ecological enhancement module to be degraded after a few years.

Appendix 7

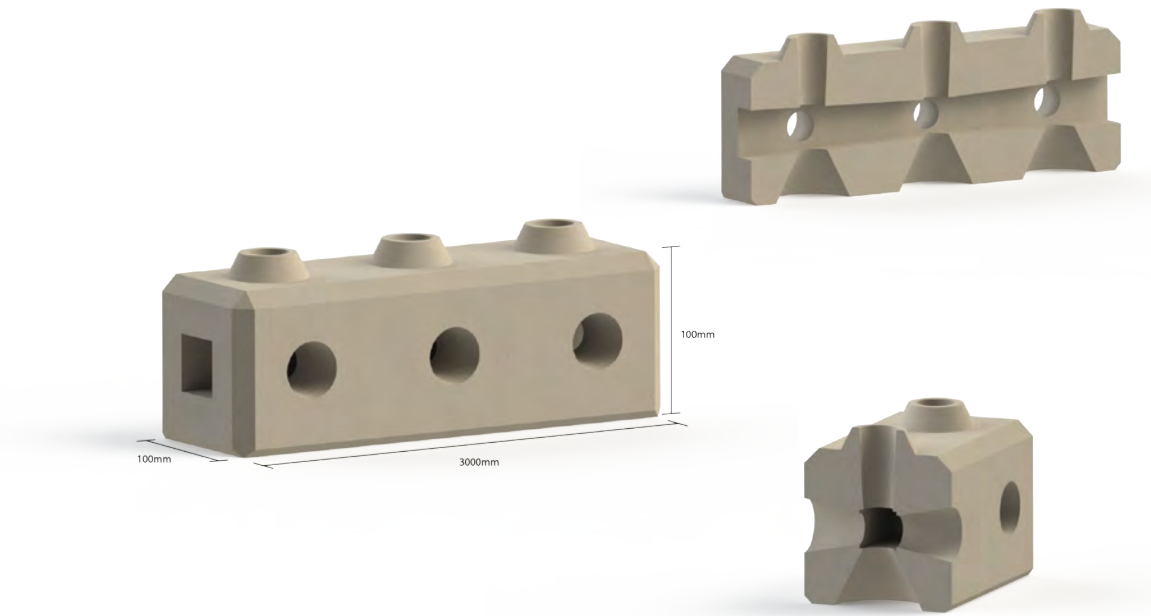
The Reefblock is shown in the top Figure. This block was used in a pilot 'Rotterdam Reef'.

During this thesis, the geometry of the block was changed. The current design is shown in the lower Figure; the EcoModule was designed according to this block.

Possible modifications to the Reefblock have been taken into account in the design of the EcoModule. Should the geometry of the Reefblock change, only the fastening method will have to be adapted and not the whole EcoModule.

The Reefblock uses an inner tubular system, the tapered cylindrical and square holes provide dissipation of wave energy (primairy function) and offer limited habitat (secondary function). The Reefblocks fit together using tapered holes on the bottom and tapered shapes on the top (margin 45mm). The blocks extract their stability from each other without using fastening methods.

First, hydraulic stones are deposited on the reef. These stones provide a flat surface on which to place the Reefblocks. Installation is done using a crane, on a boat. A software technique positions the blocks on the desired place in the REB. The crane is only capable of placing the Reefblock vertically downwards and will not be able to make horizontal manoeuvres just above the bottom surface.

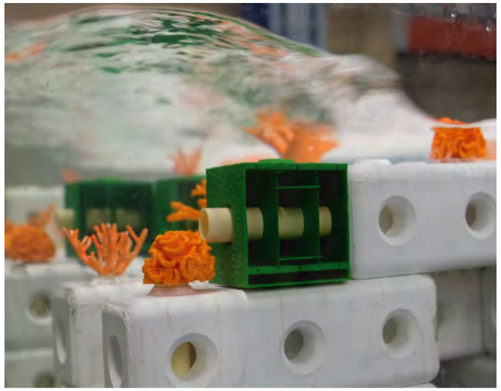


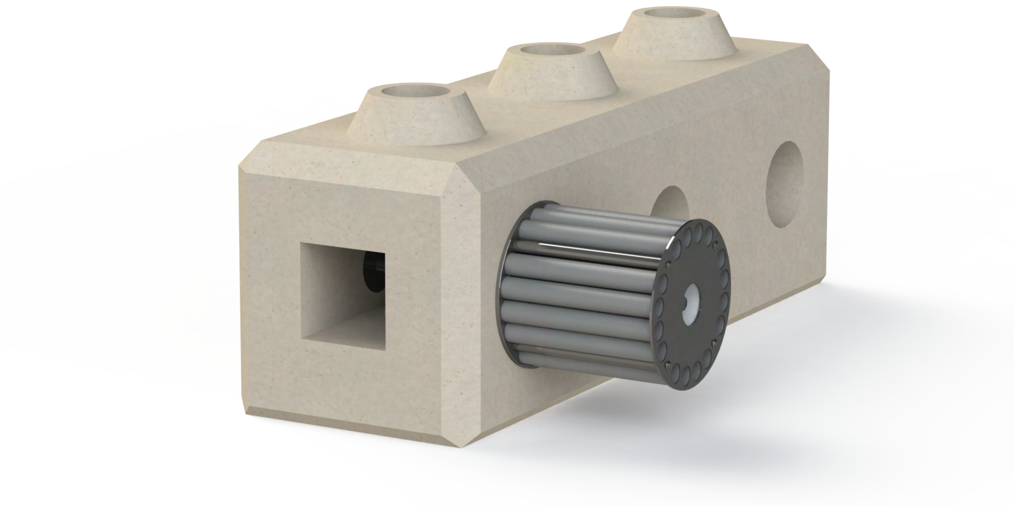
Material: low-emission cement-free geopolymer concrete
Weight: 3600 kg

Appendix 8

Appendix 9

EcoBlock	EcoModule
Shape limited to a block (high resistance, high chance of break down)	Cylindrical shape, reduced resistance
Improper attachment method, MVP broke down, low durability	Fastening method and housing made from carbon steel. Designed for tapered side tube of Reefblock
Dimensions 800x800mm	Diameter 600mm, length scalable between 600-800mm. Can be installed in more places in the REB
One configuration, not customizable	One housing, customizable using different parts. Easy to assemble
Feasibility not investigated, high investment cost for manufacturing one whole	Easy manufacturing techniques, using semi-manufactured products machined with cnc milling/turning combined with existing/easy to manufacture customization parts
No validation	Placement validated by Deltares wave simulator, Eel pond test to investigate habitat sizes and fill material
Sustainability not taken into account	Recycled steel, PVC and wood: long lifetime, use of standard existing parts/semi-finished products, modular parts





Appendix 10
Materials

All materials displayed below are bioreceptive. The primary function lies on developing additional habitat space for grazers and predators. Attracting these organisms is easier with a habitat that looks natural and a habitat that offers food (colonised micro-organisms). For this reason, the habitat was chosen to be made of a bioreceptive material.

According to Baine (2005), concrete, rocks, tyres, plastic and steel are the most common materials used in artificial reefs. Concrete is the most used material, as the Reefblocks are made of concrete, this will be abundant in the REB. The EcoModule is not a massive/solid design and therefore depends on other material properties, for example a high strength at low wall thickness.

A study has been found, showing the amount of citations of materials used for artifical reef (Baine, 2001). This study shows that concrete is the most common material, but rock, tyres, plastic and steel are also commonly used (Appendix X). Also shown is the number of papers relating specific categories of artificial reef construction to a general theme. For the fish attraction theme, concrete scores best but the above mentioned materials are also used for this. Another study proves that benthic communities (Clams, worms, oysters, crustaceans, mollusks and mussels) also colonise concrete (Becker et al., 2020). One example is the colonisation of oysters on concrete rings. Colonisation of oysters has been proven to reduce coastal erosion and boost biodiversity (Chowdhury, 2019).

Concrete is currently used for the Reefblocks. CEM III recycled concrete (Heidelberg cement group, n.d.) has been used for the first Pilot in Rotterdam. Alongside this, Reefy has investigated low emission cement free geopolymer concrete as a replacement for the CEM III concrete.This concrete variant is a more sustainable solution than the current concrete (Almutairi et al., 2021). Reefy is currently testing this form of concrete and has already proven that coral grows on the surface (Personal communication, Leon haines). This means that this form of concrete can be considered bioreceptive.

The text on the left concludes that concrete is very suitable as a material for artificial reefs. However, it should be considered whether concrete is the right material for the EcoModule. Concrete has low strength when tension is applied to it (Victor, 2020). The EcoModule is an add-on to the REB, which means that the housing of the module must be able to withstand high wave forces. For this reason, concrete is not suitable as a strucutral enclosure for the EcoModule. However, concrete is ideal as a modular component that can be used to attract producer and consumer organisms and thus grazers and predators.

The material is also very dependent on the purpose for which it is used. Accoording to Burt et al (2009), gabbro (deep rock equivalent of basalt) is preferred over concrete for coral recruitment and the material terra-cotta is well suited for the attraction of benthic communities.

Basalt rock is also suitable as a material for artificial reefs. This is shown in an experiment carried out by Rijkswaterstaat in the Netherlands. Four reefs consisting of a circular shape of basalt rocks were placed in 18 meters deep water. Within the first hour, fish, north sea crabs and starfish were spotted at the reefs. After twelve days cultivation by hydropolyps was encountered. After a month, barnacles and sea anemones were discovered and after ten weeks 80% of the artificial reefs were covered with biomass, this remained the same for over nine years. It can be said that the basalt reefs enhance the biodiversity and biomass of the area for a longer period of time. It has been proven that basalt-artificial reefs stimulated the growth of new populations and species that had been extinct from the North Sea (Jager, 2013).

These materials have similar properties to concrete which means that these materials are also suitable as bioreceptive parts for attraction or producer and consumer organism but not as housing for the EcoModule. Melting and shaping the rocks gabbro or basalt is possible, but this requires a lot of energy which is not sustainable. However, the rocks can be used as filling material. The material terra-cotta, on the other hand, is a type of clay that is very easy to work, making it possible to give it a shape that can be used as a customisable part in the EcoModule

Two other materials that Reefy has tested are Solanyl and Arboblend. Both types have bioreceptive properties due to coral growth on the materials. Solanyl is a biodegradable, carbon neutral and non-toxic material. This material is made from recycled potato starch and is incorporated into mats used for nature restoration (MaterialDistrict, 2020). Arboblend is a 100% biobased material composed of several biopolymers (Appendix X). This material is biodegradable or resistant depending on the intended application and composition (TECNARO, n.d.)

A requirement of the EcoModule is that it is not made of biodegradable materials and therefore has a high durability. Its primary function is to provide a habitat, it is therefore not intended to degrade over time. The aforementioned biopolymer Solanyl is therefore not suitable and Arboblend will have to be made with the right composition to prevent it from biodegrading.

.

According to Zhang et al (2008), microbial organism colonise on both plain carbon steel and on the layer of rust formed when submerged for long periods of time. In this test, copper, aluminium and plain carbon steel were compared. Carbon steel (with and without rust layer) had the highest number of colonisation. Complementing this is a study on the colonisation of plain carbon steel structures. In this study, it was proven that the colonisation of organisms creates a biofilm that protects steel from corroding (Southwell et al., 1974).

The concrete artificial reef has already been developed by Reefy. Plain carbon steel can be used to develop the structural housing of the EcoModule. This material is relatively cheap and has suitable properties (high yield and tensile strength, low ductility, to function as housing. At the same time, it has been proven that (rusted) plain carbon steel is colonised by marine organisms and this, due to the resulting biofilm, prevents corrosion.
Since the EcoModule is not removed from the water after installation, corrosion is not an issue. Corrosion causes the steel to 'rust solid' which is then colonised and protected by organisms

Wood is widely used for artificial reefs because of its low cost, lack of toxicity and good compatibility with marine environments (Guo et al., 2021). This study investigated whether microbial communities, groups of microorganisms that share a common living space, colonise the materials concrete and untreated wood (Populus). This test showed that concrete was the most colonised and wood matched it. For some micro organisms, such as benthic communities, the results were similar.

The degradation of wood in salt water is largely caused by contact with oxygen, wood-decaying organisms thrive primarily on the water surface, where there is an abundance of atmospheric oxygen, soil moisture, and nutrients available (Levy, 1987). However, when the wood is in a water-logged/aquatic environment, degradation will proceed at a slower rate and will therefore survive for an extended period of time.

This indicates that wood is a suitable material for the EcoModule. Wood is an organic material that is beneficial for sustainability, it is cheap, easy to work with, degrades slowly (when waterlogged) and allows colonisation. The mechanical properties of wood, in terms of strength, are lower than those of carbon steel. This means that wood can be used as a customisable part and not as an housing that absorbs forces from the sea. Besides populus wood, low-cost variants such as, spruce and pine can also be used.

The use of PVC in artificial reefs is also possible. Accoording to Brown (2005), PVC, along with concrete, scores high in terms of microbial colonisation; crustaceans, molluscs, annelids and bryozoans were found on the PVC surfaces. Steel, wood and rubber were also tested in this study. Colonisation on rubber was lowest, while steel and wood scored average.

PVC does not have the suitable mechanical properties to withstand wave energy, but it does offer the possibility of colonisation by micro-organisms and can therefore be used as a customisation part. In addition, this material is very cheap and easy to process. Given the design of the EcoModule, PVC pipes are very suitable.

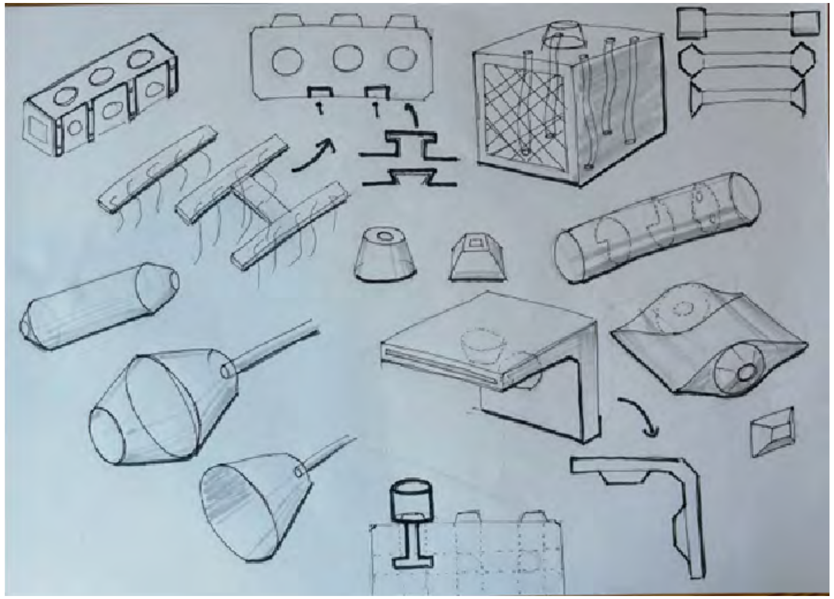
One of the most innovative ideas regarding the development of an artifical reef is the creation of limestone. A steel structure is installed in the water and electrified with a low voltage, which causes dissolved minerals to be converted to the limestone that will grow on steel surfaces. This structure is free in size and shape, is self-repairing and gets stronger over time (Goreau & Prong, 2017). However, it does involve high installation costs.

Because of the high cost, this method is not cost-effective for Reefy. The installation and constant energisation result in high costs. One idea was to put the EcoModule in a lab at a voltage for a period of time that boosts the initial creation of limestone, which is then placed in the sea. Again, this idea will add up in cost and will take a lot of time in the process. However, this way will be named as a recommendation because it may also be conducive to the fastening method.

To conclude, low carbon steel will be used for the structural parts of the EcoModule. A combination of Populus wood and PVC will be used for the customisation parts. These materials are being colonised in large numbers by eel prey (benthic communities)

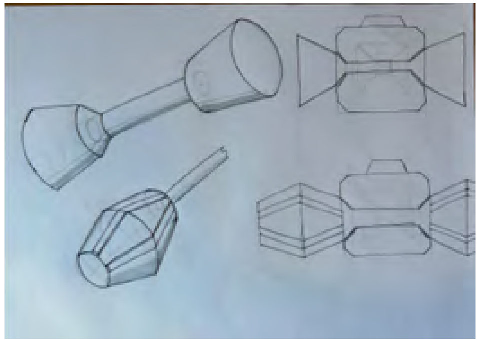
Appendix 11

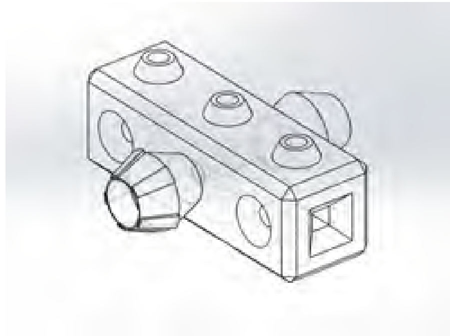
After the research phase, the ideation phase started. On the basis of the first requirements, a pressure cooker was conducted. This 30-minute creative session generated several ideas.



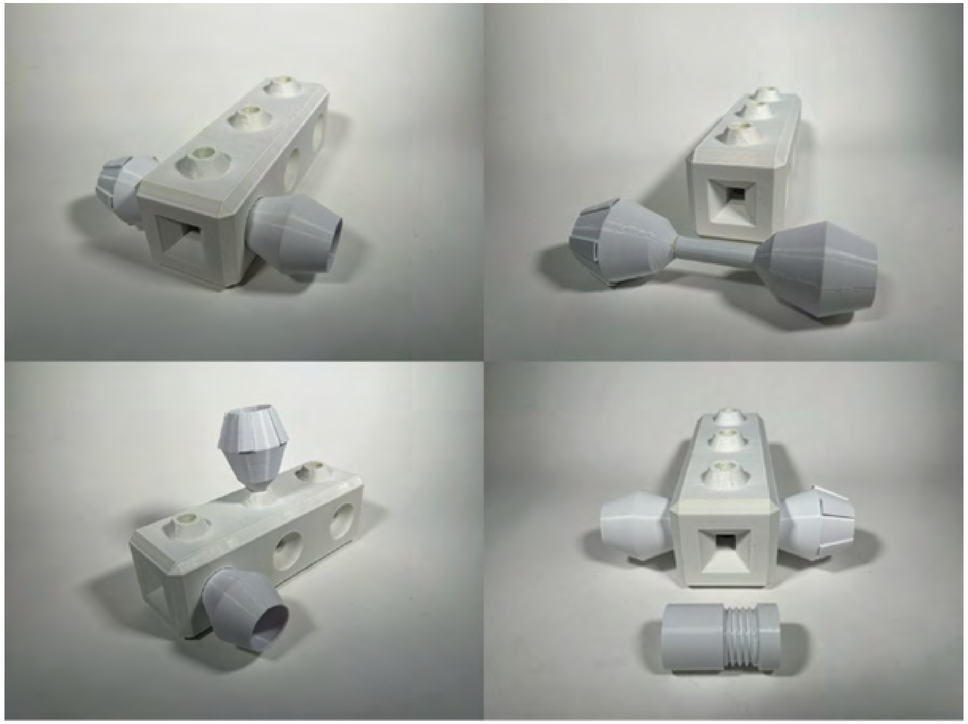
Some of these ideas were further developed and divided into Module ideas and fastening ideas.

Idea 1
The idea below are two cone shapes connected by a cylinder through the Reefblock. This shape was chosen because it offers less resistance to sea currents. A variation on this idea is a cocoon shape; the narrow corridors on the outside of the housing illustrate the possibility of expansion, for example, as a shelter for small organisms.

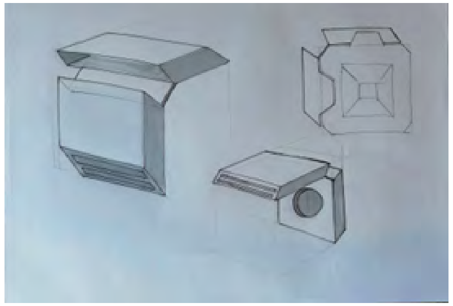


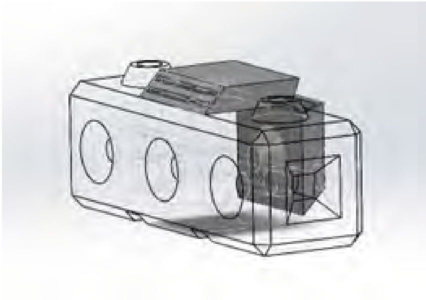


After 3D printing the part, several possibilities of placement and an idea for the connection of the ends emerged.



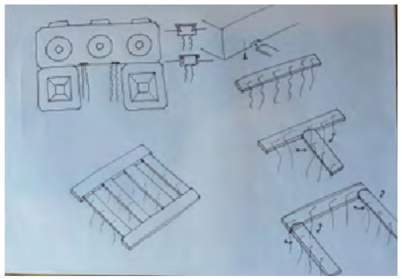
This habitat, to be secured with a click system, is born from a different mindset. Here, the product does not use the inner tubular system but the outside of the reefblock as attachment point. After 3D printing, it was immediately noticeable that this product clicked nicely onto the reefblock but that the choice of material is important, a rigid material is needed for idea. The product features a grid that provides water inflow, which can be modified if species like running water or quiet, calm water. This solution offers two habitats in one product and requires no fastening methods.

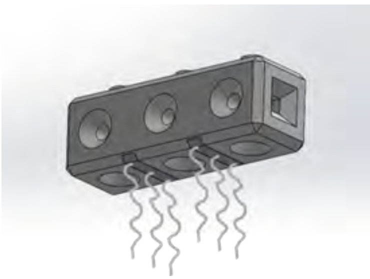




Idea 3

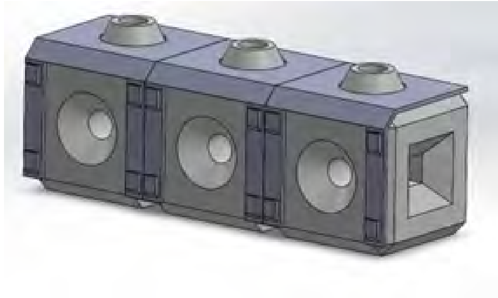
This idea was developed for the slots (for fork lift) at the bottom of the reefblock. Here, parts can be inserted and attached to which biore-ceptive/habitat materials can then be hung. This idea could be interesting as it is a very cheap solution and makes good use of space. The housing can be formed by the Reefblocks and the habitat can be created with the sliders. Due to a change in the geometry of the Reefblock, this option is no longer possible. Should the slots reappear in a redesign, this idea can be considered a recommendation. However, this does exemplify simplicity and makes good use of the shape of the Reefblock.





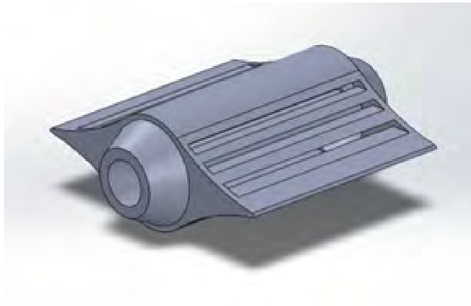
Idea 4

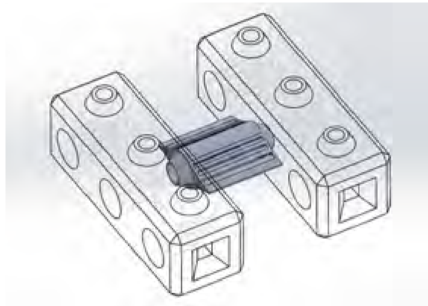
The design of the Reefblock is not complex, offering no fastening point apart from the inner holes. The next idea is an addition that adds fastening points to the block. This solution made of steel is placed over a reefblock and is held in place when another block is put on. The solution can provide many options for fixing the module.



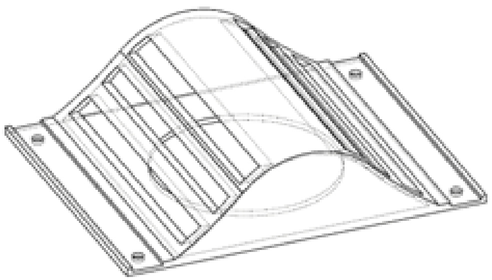
Idea 5

Different shapes have also been considered; the figure below shows a droplet-shaped habitat attached between two Reefblocks. Again,a grid can be seen to allow water intake. Here, a droplet shape was chosen to minimise resistance to sea currents.



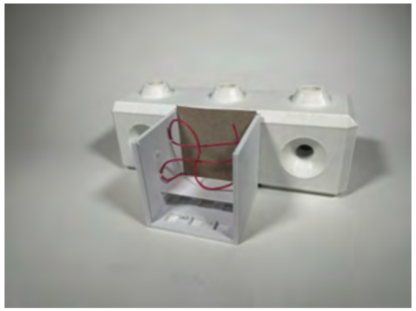


Idea 5b
This waveform, derived from idea 5, can be placed on top or on the side of a reefblock. This shape was chosen to create as little resistance as possible to the sea current and thus reduce the chance of breaking the habitat. The part can be secured with straps or drilled into the reefblock.



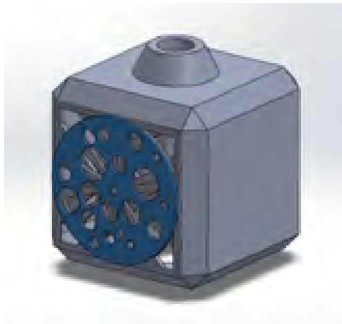
Idea 6

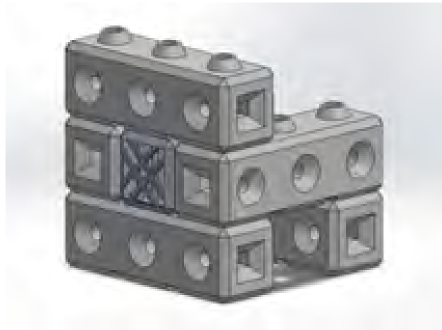
A basic idea that allows for different configurations. Fastening parts are placed in different places for placing shelves, ropes can be tensioned and the housing can be adjusted. The idea is assembled with precise fits, which keeps the whole product together



Idea 7

The next idea is a third part of the Reefblock, inspired by the EcoBlock. This block is attached in the same way as the Reefblocks. Different configurations can be created using discs that can be placed on the module, which allows the access to the block to vary. In this way, it can be determined which species can and cannot enter the block. Internally, bars have been placed to fill up space in the block, create different spaces and makes the appearance more natural, inspired by trees in a forest





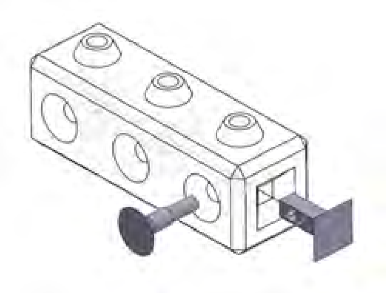
Fastening ideas

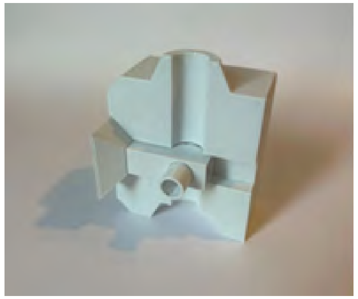
In this section, the ideation phase about attaching the module to the Reefblock is described.

One of the first requirements around the placement of the EcoModule already arose in this phase; The EcoModule cannot be attached to the bottom of the Reefblock, because the Reefblock are stored in the orientation in which the Reefblocks are placed in the water. If the EcoModule would be attached to the bottom it must be done when the crane lifts the Reefblock, due to safety regulations no one is allowed to stand under the Reefblock.

Fastening method 1

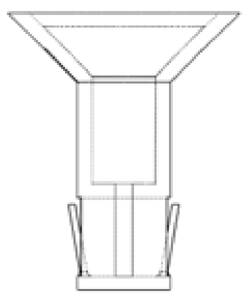
A fastening method that consists of two parts sliding into each other, a strong connection, however, they are not fastened. The method uses multiple entrances of the inner tubular system resulting in two different parts, while the volume of the parts is very high.

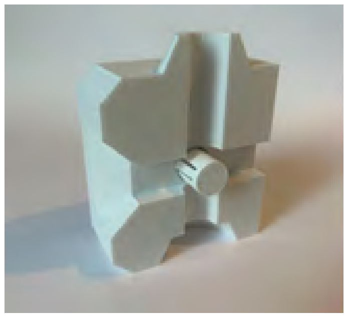




Fastening method 2

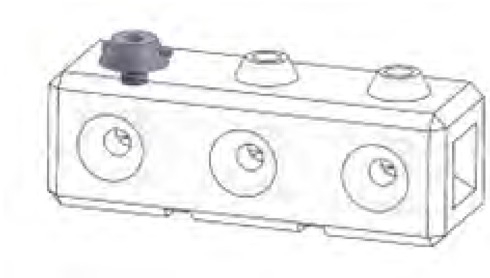
A user-friendly click method ensures that the module is fixed with one part. However, this design direction is complicated and expensive.





Fastening method 3

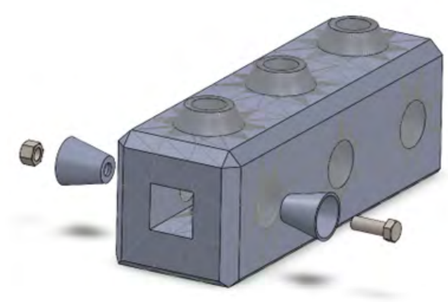
A deep-drawn shape designed to attach the module to the top. This 'hat' is secured with a pin that runs through both the part and the Reefblock, this does require drilling. The hat is placed on the top left, however I found out that this is not a possible location.



Fastening method 4

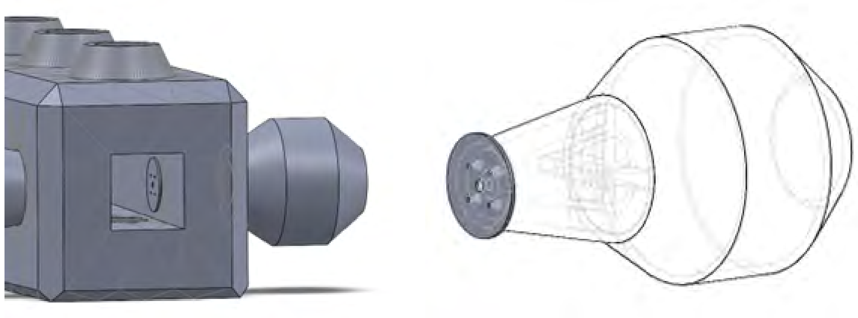
The following fastening method was developed for the new Reefblock (See 2.4 Challenges:Adjusted geometry of Reefblock). The new tapered/conical shape of the Reefblock brought the following idea. The tapered attachment part fits precisely into the side hole. By placing these on both sides, they can be secured using a bolt and nut.

This solid connection pulls the two tapared shapes towards each other where. The higher the pulling force, the higher the frictional force (between fastening part and tapered shape) which ensures that the module will not rotate. It is important that the shapes fit tightly together



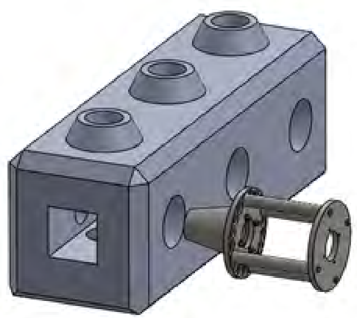
Fastening idea 5

An alternative is to secure the cone with a plate on the inside of the block. However, this is detrimental to the assembly because the fastening then has to be done from the inside.

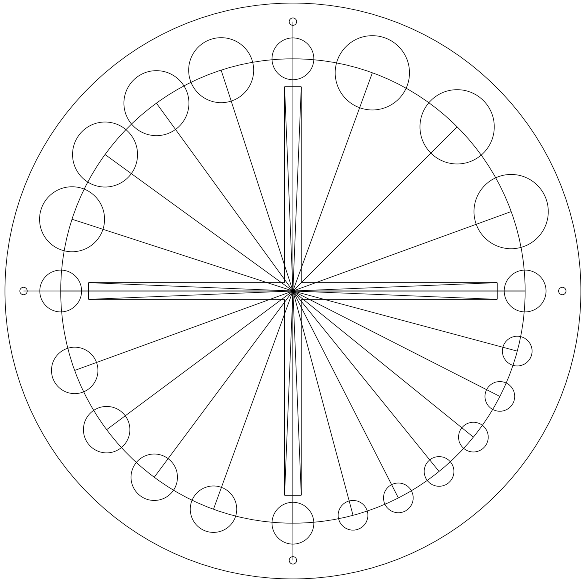
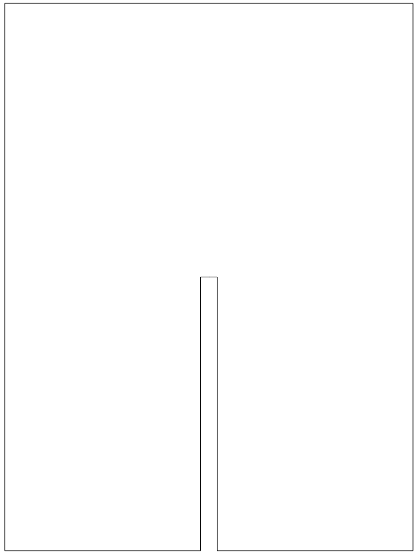
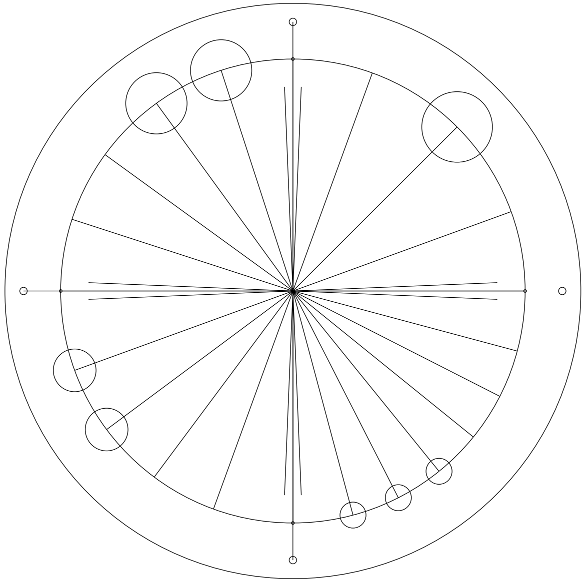
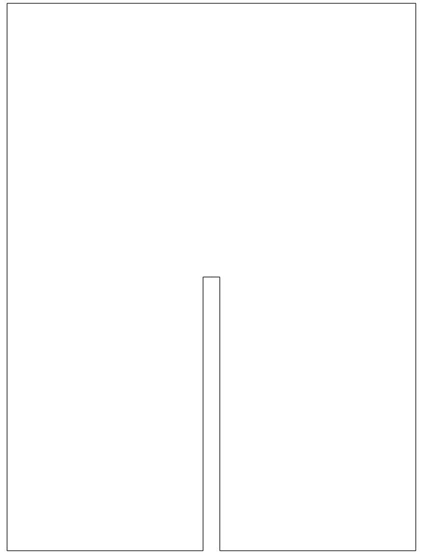
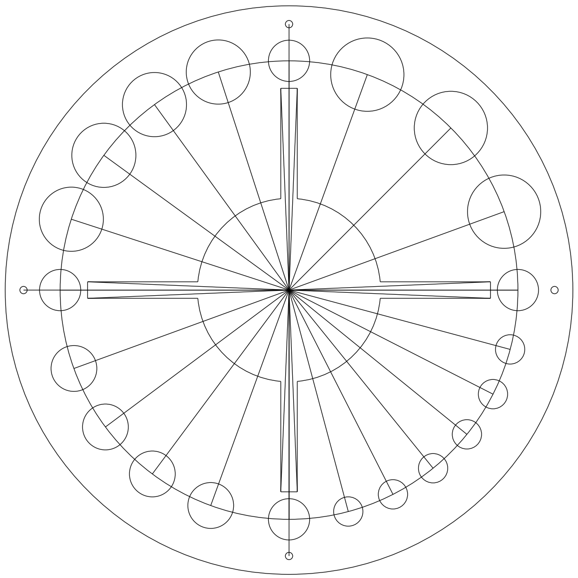
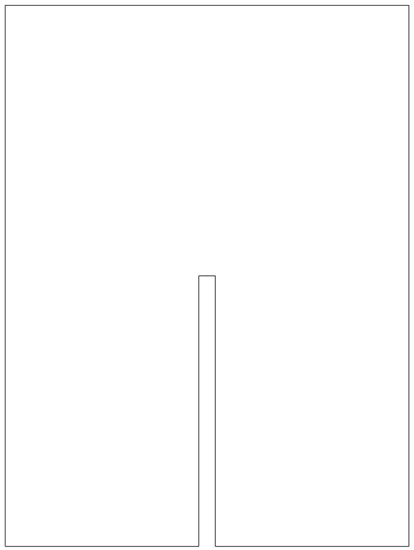
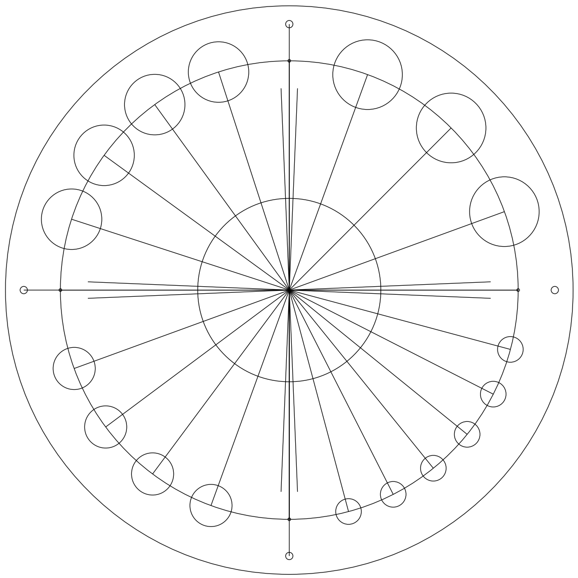
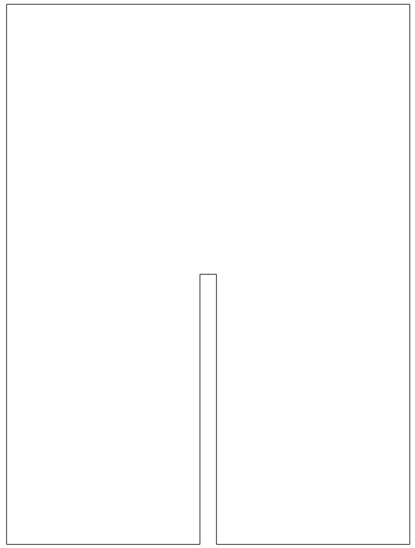


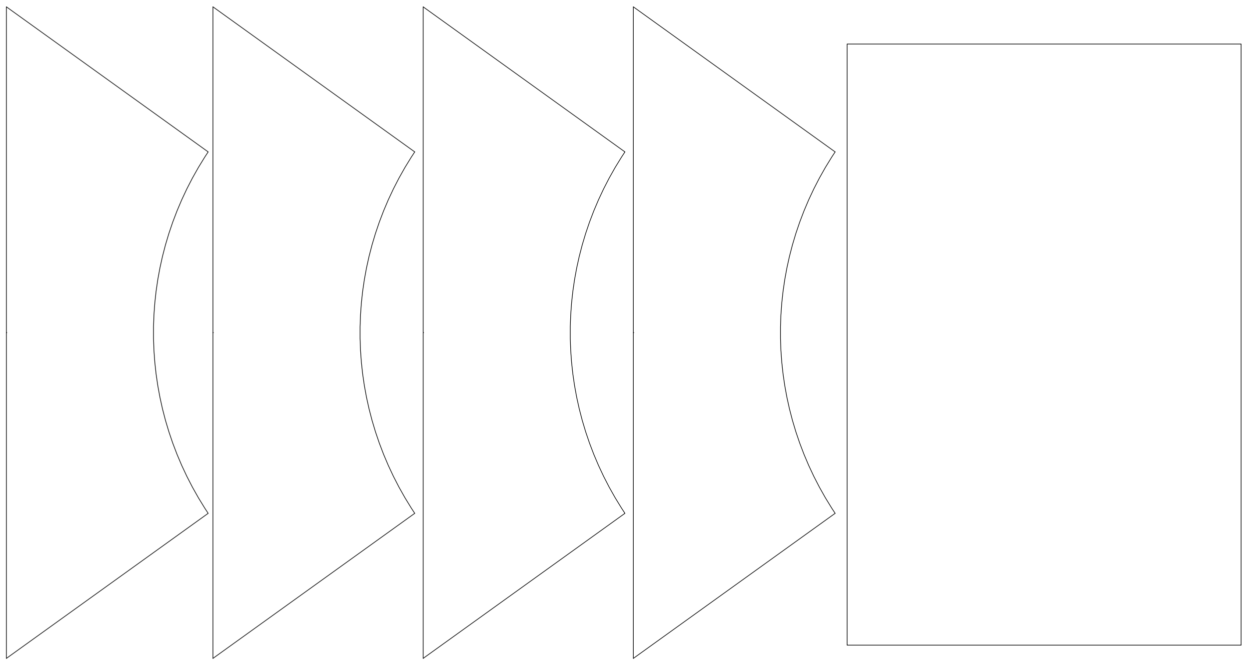
Fastening idea 6

The conical shape also makes it possible to attach the module without fasteners. The shape has to be pushed into the conical hole of the Reefblock with a certain force. If the parts fit together exactly without margin, the friction between the materials will ensure that the module remains fixed. For this method, the angle of the tapered schape should be 8 degrees maximum (Schumacher, 1992), which is not the case with the Reefblock, i.e. 11.3 degrees, and therefore this method will not work. However, when the Reefblock is redesigned, this can be taken into account in the design process.

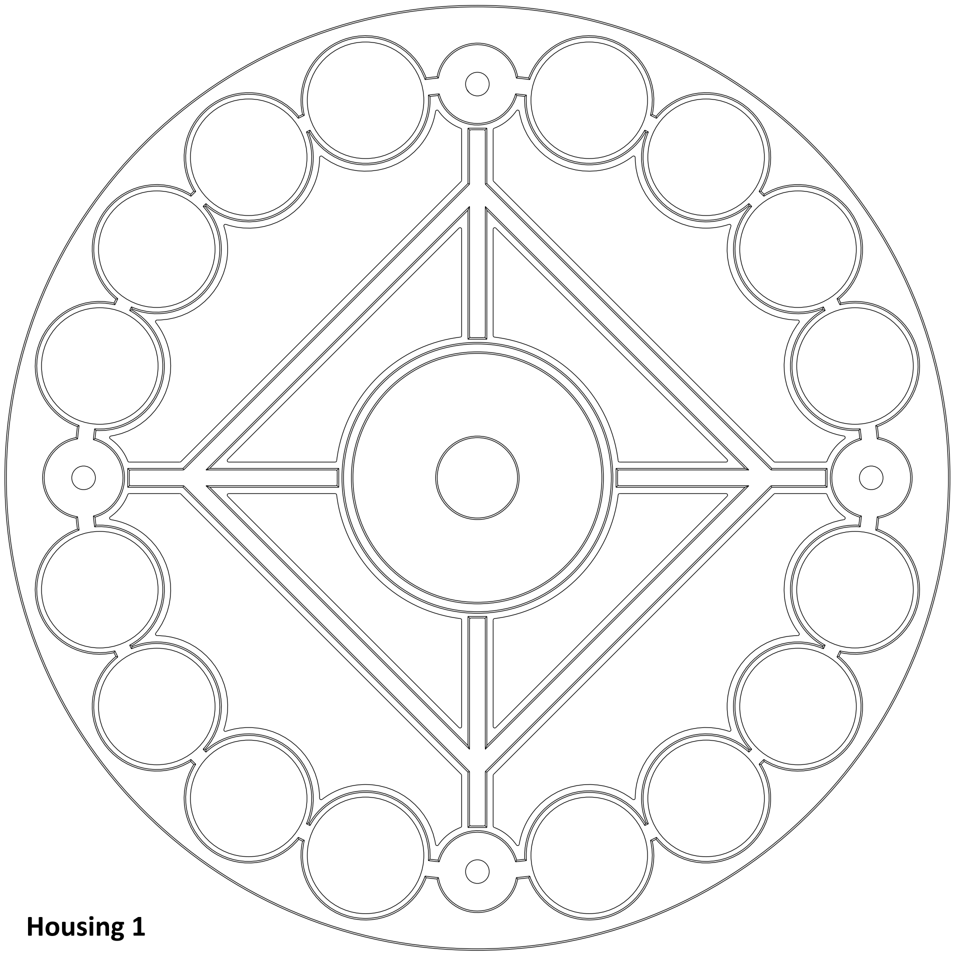


Appendix 12

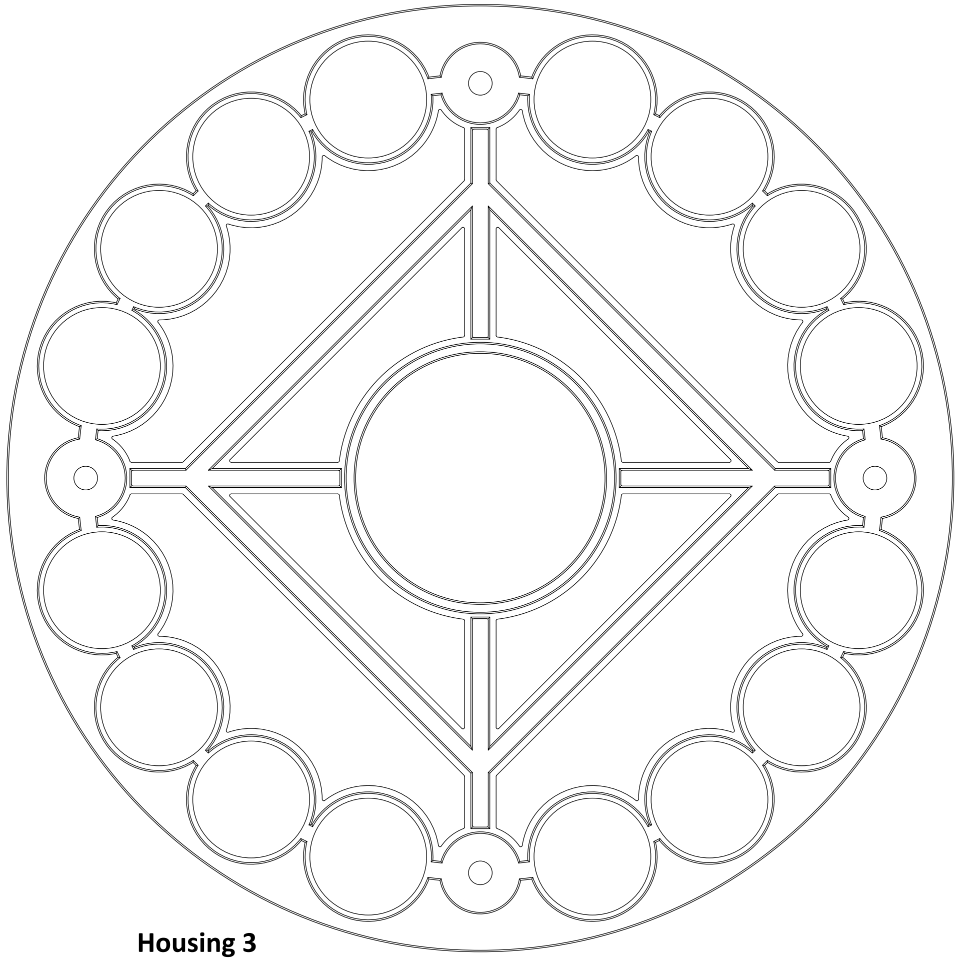











Appendix 13



Housing 1



Housing 3

Appendix 14

The EcoModule	amount	Weight (kg)	Price/kg	price/st	Price	Source
Materials						
Structural parts						
Module						
Housing 1	1	14,8	1,15	17,02	17,02	Granta Edupack, 2023
Housing 2						
Tubes	4	1,39	1,15	1,5985	6,394	Granta Edupack, 2023
Welding socket male	4			2,3	9,2	https://catalog.anchorfluidpower.com/viewitems/weld-couplings/socket-weld-pipe-to-male-jic-couplings
Welding socket female	4			2,3	9,2	https://catalog.anchorfluidpower.com/viewitems/weld-couplings/socket-weld-pipe-to-male-jic-couplings
Housing 3	1	10,1	1,15	11,615	11,615	Granta Edupack, 2023
M15 bolts	4			0,1	0,4	https://cnjujiangwujin.en.alibaba.com/minisiteentrance.html?spm=a2700.details.0.0.2efe4117cJUyGO&from=detail&productId=1600718398462
Fastening parts						
Fastening part 1	1	5,95	1,15	6,8425	6,8425	Granta Edupack, 2023
Fastening part 2	1	14,4	1,15	16,56	16,56	Granta Edupack, 2023
M48 Flange hex nut	2			14,4	28,8	https://www.orbitalfasteners.co.uk/products/m48-nyloc-nut-steel-bright-zinc-plated-grade-8-din-985-type-t
M48 Threaded rod	1			45,32152	45,32152	https://smoldersbv.nl/schroeven-en-bouten/draadeind/draadeind-blank-8-8-1m-1/5975zw88481m-m48-x-1000-mm-1st/?gad_source=1
Customisation parts						
Main tube	1	1,7	2,2	3,74	3,74	Granta Edupack, 2023
PVC tubes	16	0,38	2,2	0,836	13,376	Granta Edupack, 2023
Wood panel a	2	0,44	1,01	0,4444	0,8888	Granta Edupack, 2023
Wood panel b	2	0,83	1,01	0,8383	1,6766	Granta Edupack, 2023
Material cost sub total					**171,0344**	
Labour and machinery						
Module						
CNC machining housing 1					150	Personal communication, employee PMB industrial design engineering
CNC machining housing 2					150	Personal communication, employee PMB industrial design engineering
Fastening parts						
CNC turning fastening part 1					10	Personal communication, employee PMB industrial design engineering
CNC turning fastening part 2					10	Personal communication, employee PMB industrial design engineering
Customisation parts						
Cutting					5	Personal communication, employee PMB industrial design engineering
Assembly						
labour cost					2,67	Assumption own experience +/- 10 min
Labour and machinery cost sub total					**327,67**	
Total cost 1 EcoModule					**498,7044**	

Appendix 15

$\Delta l = \alpha * l * \Delta T$

Δl = the change of length
α = linear expansion coefficient
l = length
ΔT = temperature difference

Steel
Δl= 12*0.6*17=122.4 µm=0.1224 mm

PVC
Δl= 80*0.6*17=816 µm=0.816 mm

Wood
Δl= 8*0.6*17=8.16 µm=0.0816 mm

Boardshortz (2023)
Tosec (2023)