DESIGN FOR BIODIVERSITY: Enhancing Biogenic Shellfish Reefs

Justė Motuzaitė

MSc Integrated Product Design

Delft University of Technology
Faculty of Industrial Design Engineering

March 19th 2023
Delft, The Netherlands

Supervisory Team
Chair
Prof. dr. ir. Bakker, C.A.

Mentor
Dr. Faludi, J.

Company Mentor
Gwenaël Hanon

Many sincere thanks to my team of supervisors, Conny, Jeremy and Gwenaël, who have helped me and guided me throughout this project with their amazing insights and advice or just by thinking along with me. Thanks to Ernst Schrijver for his help, shared knowledge and feedback on the ideas and offshore context. Also big thanks to all the ARK Rewilding Nederland North Sea team for welcoming me and sharing your knowledge with me. And thanks to Modestas for his patience and amazing support.

SUMMARY

Biogenic reefs built by mussels, oysters or other reef-building species are one of the most important biodiversity hotspots for estuarine and marine ecosystems providing food, shelter, and breeding grounds for a wide array of species. In the North Sea, one of the most important biogenic reef builders and ecosystem engineers is the European Flat Oyster. However, due to harmful fishing practices, habitat destruction and diseases, this once-abundant bivalve is now ecologically extinct and cannot provide crucial ecosystem services.

If left without active intervention, oyster reefs have too few chances of regeneration, due to the current state of the seafloor in the North Sea and too few individuals in the environment. Therefore, active intervention is needed to bring back the shellfish reefs in The North Sea. Offshore windmill farms provide a refuge for marine ecosystems from fishing activities, which poses an important opportunity for biogenic reef restoration practices.

To understand the context of biogenic reef restoration better, multiple interviews with marine biology and ecology experts from ARK were conducted followed by a literature review and two field trips related to young oyster deployment to The North Sea. The gained insights were used to create a list of 12 design criteria grouped into four categories: Oyster survival, Scalability, Broader ecological success, Handling & deployment. According to these criteria, most of the current practices underperform in scalability due to high manufacturing, and operational costs, or provide inefficient oyster protection which hampers the success of shellfish reef restorations. Therefore, the design challenge to improve scalability and oyster protection has been chosen as the priority.

Multiple design directions and ideas have been explored using Research by Design approach while employing Whole System Mapping and Biomimicry methods with Low- and high-fidelity prototypes. Using an iterative approach and evaluating the design ideas, the solution space has been narrowed down to a final design, the unit: two steel frame gabions are connected in a double-diamond position and placed between two display pallets with all assembly tightly secured with a cotton lashing. Multiple assemblies are connected in a row with a leading rope attached to an anchor. When the ship sails, the anchor is thrown out on the seafloor and eventually pulls all units down to the seafloor.

The final design was evaluated according to the same 12 criteria. In comparison to previously discussed solutions, the final design is more scalable in terms of costs and time for larger marine restoration areas and focuses on finding balance throughout the design criteria instead of being only effective in certain aspects. In addition to introducing back the Flat Oysters, the new structures provide various microhabitats for a wide array of other benthic species to grow or shelter from the water currents, amplifying positive effects on the marine ecosystem.

Several theoretical and structural integrity tests have been done to determine the effectiveness of the new design. Further research, such as offshore field studies, is needed to determine how this new design affects young oyster survival and other benthic species.

TABLE OF CONTENTS

Chapter 1: Project Definition 5
1.1 What was it like before: marine biodiversity and biogenic reefs 6
1.2 The problem 7
1.3 The opportunity 9
1.4 The stakeholders 10
1.5 Design vision and goal 11

Chapter 2: Context Analysis 12
2.1 Methodology 13
2.2 The sea 14
2.3 The land meets the sea 22
2.4 Design requirements 26
2.5 Current approaches 28

Chapter 3: Design Direction 34
3.1 Methodology 35
3.2 Biomimicry to design 36
3.3 Shells bound with a medium 37
3.4 Shells bound with external structure 38
3.5 Evaluation 40

Chapter 4: Concept exploration 42
4.1 Whole System Mapping 43
4.2 Concept exploration 46
4.3 Testing 52
4.4 Advantages & disadvantages 59
4.5 Final evaluation 62

Chapter 5: Final design 64
5.1 Oyster survival 65
5.2 Scalability 69
5.3 Broader ecological success 72
5.4 Handling & Deployment 77
5.5 Final design evaluation 81

Chapter 6: Conclusions 83
6.1 Comparison with the current solutions 84
6.2 Limitations 85
6.3 Recommendations & future research 86
6.4 Personal reflection 86

References 89

Appendix A: Design direction - detailed progress 94

Appendix B: Concept exploration – process and interim ideas 107

CHAPTER 1:
PROJECT DEFINITION

1.1 What was it like before: marine biodiversity and biogenic reefs

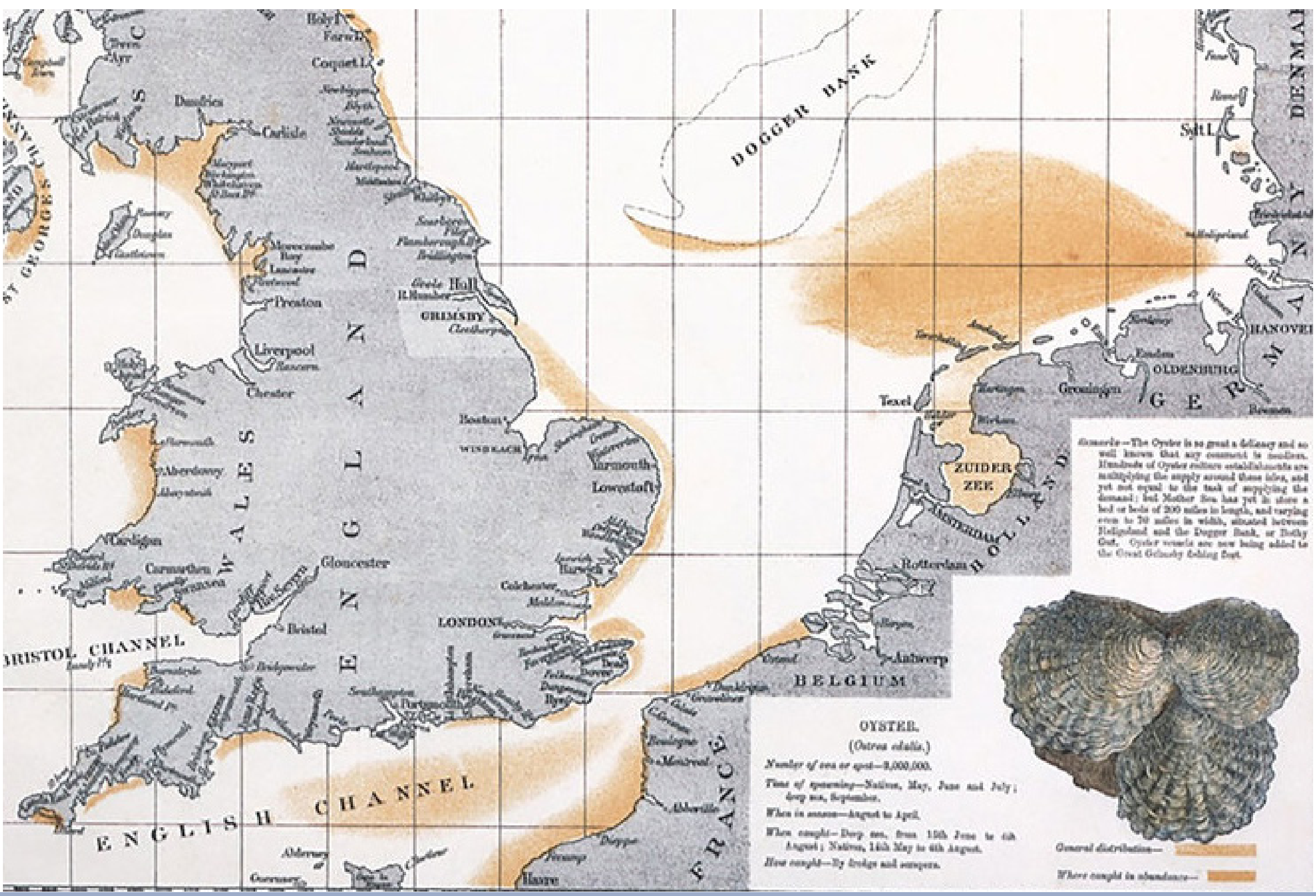
1.2 The problem

1.3 The opportunity

1.4 The stakeholders

1.5 Design vision and goal

Entry for O. edulis in Olsen's (1883) Piscatorial Atlas of the North Sea. Oyster beds marked in orange.



1.1 What was it like before: marine biodiversity and biogenic reefs

As lush green forests are considered to be the biodiversity hotspots for biodiversity on land, so are the biogenic reefs for estuarine and marine ecosystems (Gaspar et al., 2011; Pogoda et al., 2019). Biogenic reefs are built by oysters, mussels of other suspension feeders: by growing on top or next to each other, shellfish create complex geomorphological structures. In the North sea, these structures offer a rare hard substrate in mostly sandy seabed, which provides feeding, hiding and breeding places for wide array of other marine species (Figure 2). For example, a study in coastal 'Voordelta' area showed that 60% more benthic species (organisms living on/in the seafloor) occur on the shellfish reef than on sandy areas (Christianen et al., 2018).

Records from the 19th century show that ~30% of the North Sea floor was covered with native shellfish reefs (see Figure 1), which provided numerous surface irregularities, gaps, and cracks to cater to a wide variety of different marine organisms' living and feeding preferences. In addition to providing a diverse habitat and food source for other species, shellfish reefs filter great amounts of water, which reduce excess nutrients and pollutants as well as clear the water. The main ecosystem benefits are summarized in Figure 4.

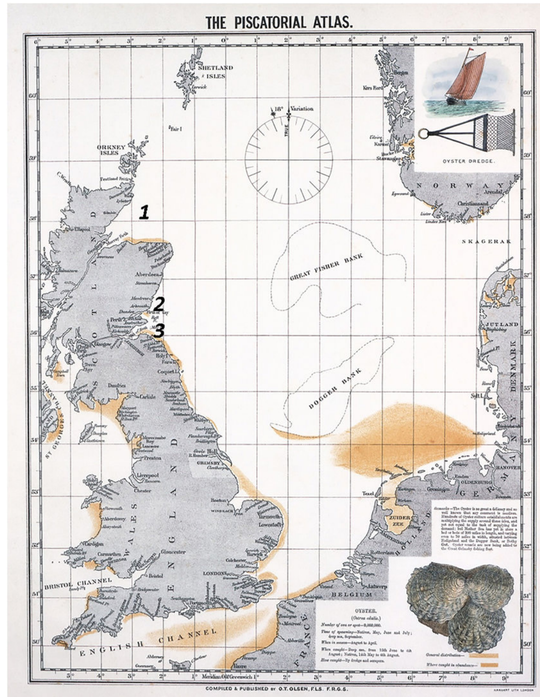


Figure 1: Entry for O. edulis in Olsen's (1883) Piscatorial Atlas of the North Sea. Oyster beds marked in orange.

Figure 2: Voordelta oyster reef with native Flat oyster, Pacific oyster, mussels and macroalgae (Didderen, 2020). Image credits: Floor Driessen Bureau Waardenburg.

1.2 The Problem

The North Sea is one of the busiest seas in the world: surrounded by eight densely populated countries, it is full of human activities, such as fishing, shipping, oil and gas exploitation, wind energy, extraction of sand and gravel. Together, these various activities have damaged local ecosystems, of which only a few remain in their natural state (Álvarez et al., 2017; Halpern et al., 2008). Fishing practice known as 'Bottom trawling', is regarded as one of the anthropogenic activities inflicting the most damage to the seafloor (Depestele et al., 2018), see Figure 3. Due to these overfishing practices, habitat destruction and diseases, native oysters have been pushed to ecological extinction in the wild marine environments. Recently discovered Voordelta native oyster reef only covers 0.4 km2 compared to over 25000 km2 Dutch North Sea area occupied by native oysters in the 19th century (Christianen et al., 2018) – a small fraction.

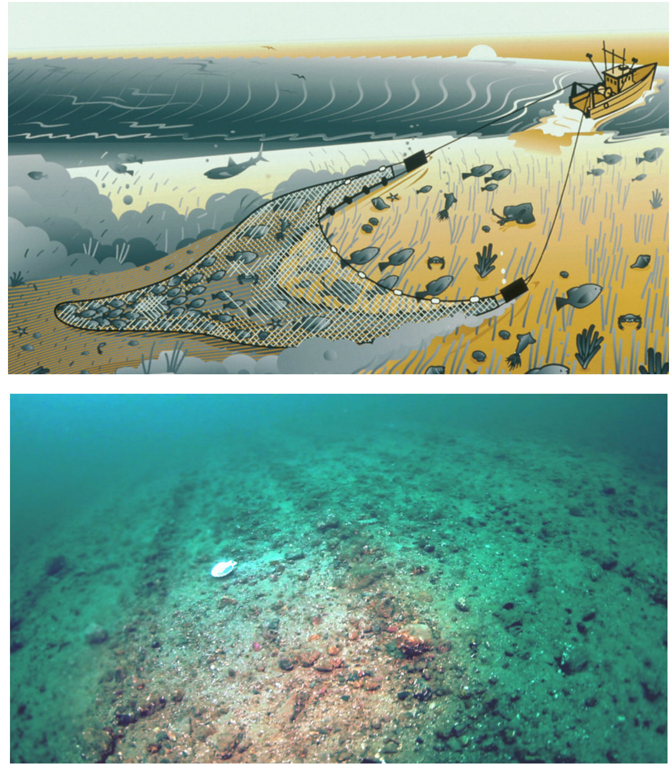


Figure 3: Top - Bottom trawling practice illustration, Bottom - the seabed after bottom trawling fishing. Trawling practice can be very destructive to the environment, not only many unwanted marine species are caught and thrown away, but the habitat is being destroyed, leaving nothing behind. The seafloor then resembles a deprived agricultural land – an ecological desert (Stiles et al., 2010, ARK Rewilding Nederland, 2022). (Photo credits: Freiwald et al. 2004; Open Seas, 2021).

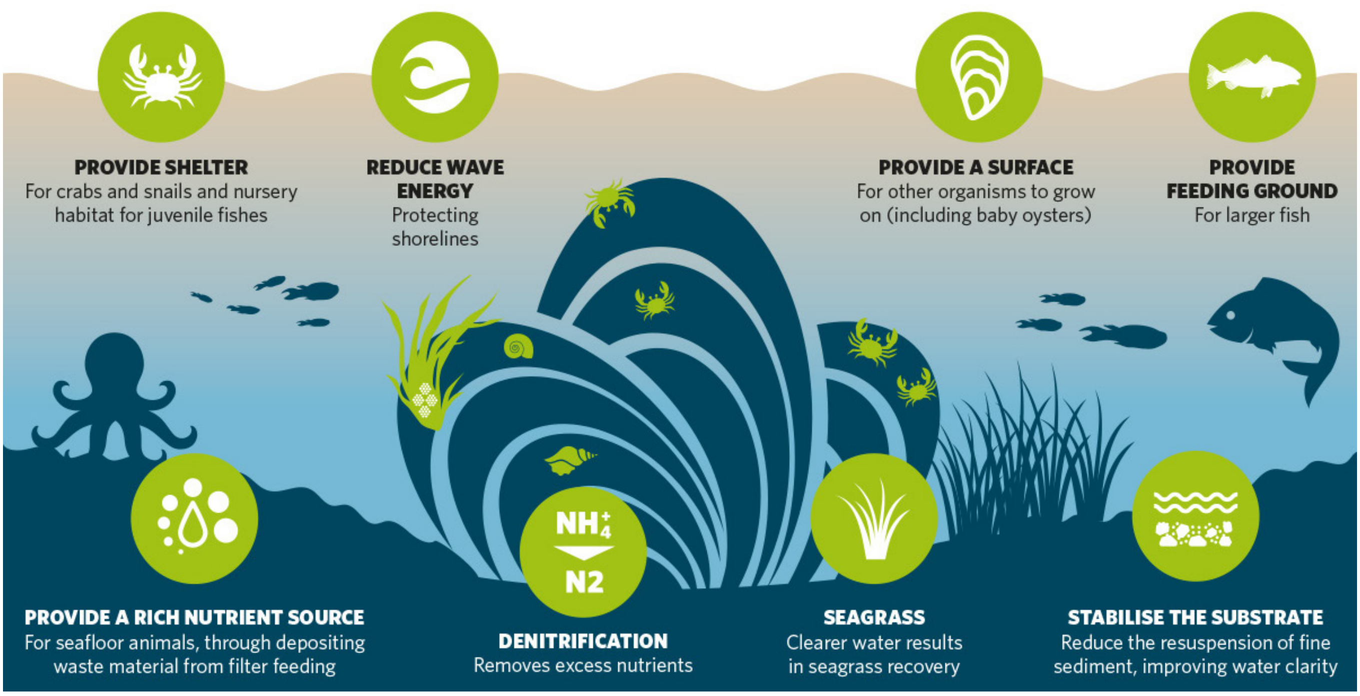


Figure 4: Functions provided by intact oyster reef habitats. Image credits of Fitzsimmons et al. 2019.

Current North Sea ecosystem is out of it's equilibrium: due to human activity, the hard surface of biogenic reefs has disappeared, leaving large parts of the seabed with sandy or silty soft substrate (see Figure 5) (Hofstede et al., 2022). This kind of environment introduces difficulties for young shellfish larvae to survive and grow: there is no hard surface for larvae to cling on and stabilise themselves, on top of that, the bottom sea currents are stronger without any barriers to slow them down (ARK Rewilding Nederland, 2022). This type of new environment hosts different and less diverse epibenthic species community compared to the one which lives on hard surfaces (Hofstede et al., 2022).

The situation can be described as a looped problem: shellfish cannot cling to the seabed and start forming the reef because there are no natural structures, such as reefs, which would slow down the currents and provide a solid base to attach. In this degraded ecosystem, and intervention must be done to encourage more significant ecosystem regeneration.

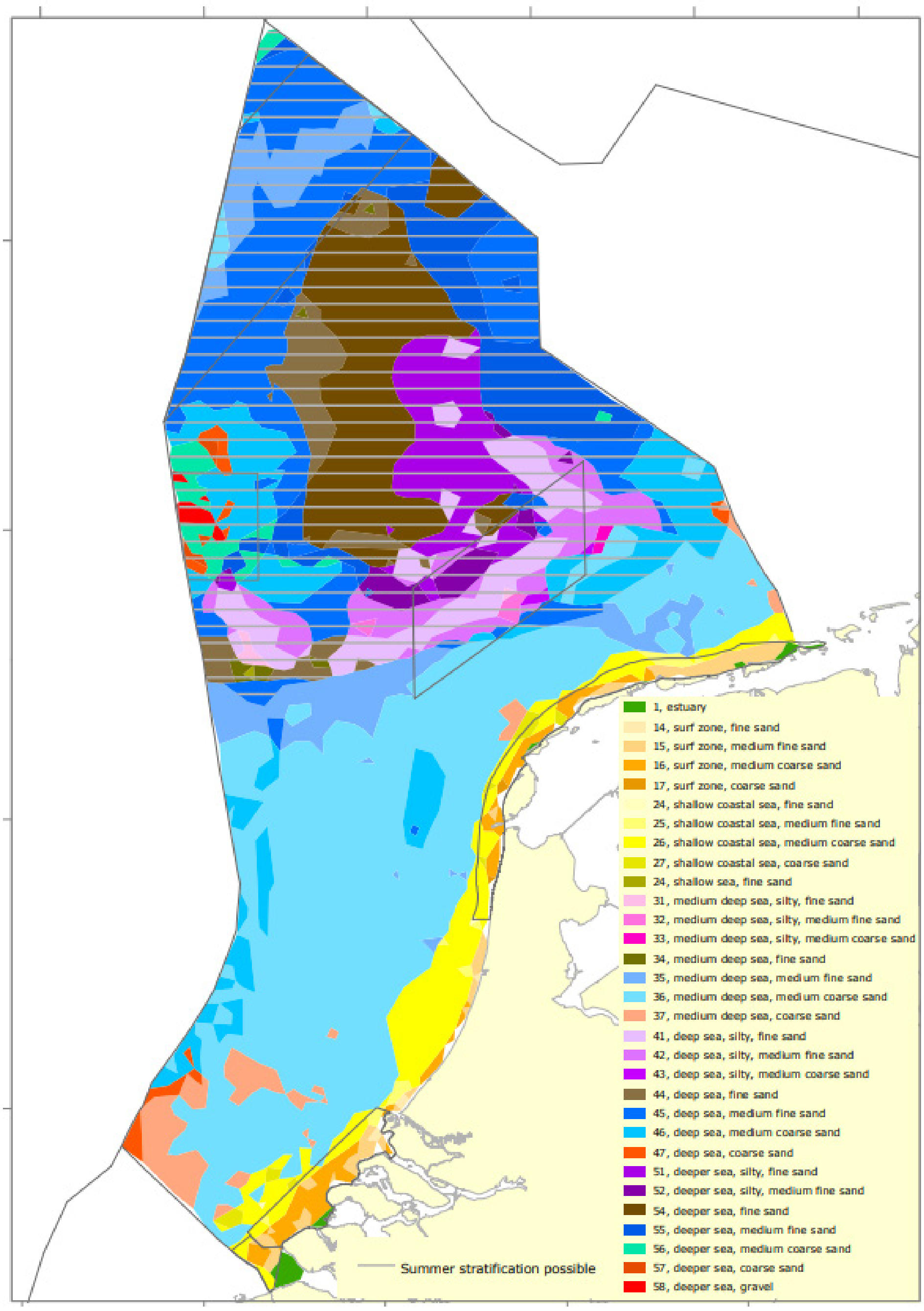


Figure 5: Habitat types in the North Sea mapped by Bos et al. (2011). Small red color in the upper part marks gravel sediment, all other colors mark different types of sand.

1.3 The opportunity

Offshore Windmill Farms

More and more countries are turning to renewables for a more sustainable energy production – one of the most competitive renewable sources is the wind power. The North Sea has been the busiest sea in Europe – 77% offshore windmill farms in Europe have taken place here (WindEurope, 2020). Currently the area occupied by offshore windmill farms in the North Sea basin is around 8500 km^2 and is expected to grow 9577 km^2 in 2027 (Gușatu et al., 2021), see Figure 6.

The development of offshore windmill farms does not come without ecological cost: habitat loss, construction phase causes more underwater noise and water vibration, which can negatively affect marine species and their hearing abilities, these farms can also act as a barrier and disturb migratory bird connectivity between areas for foraging and breeding (Gușatu et al., 2021).
At the same time, the offshore windmill farms provide some very interesting ecosystem conservation and regeneration opportunities: Offshore windmills had a positive effect by introducing rigid structures to the seabed, on which various species can grow according to vertical zonation, see Figure 7. Especially the scour protection, used to minimize the sediment hole formations around the monopile, is considered to have significantly positive effect on benthic and epibenthic species. Fowler et al. (2019) found that species composition on the windmill structures near the seabed is more similar to the natural rocky reefs. However, this monopile-as-artificial-reef effect is limited due to the large distance which the windmills need to be apart, most of the time 500-600 m.

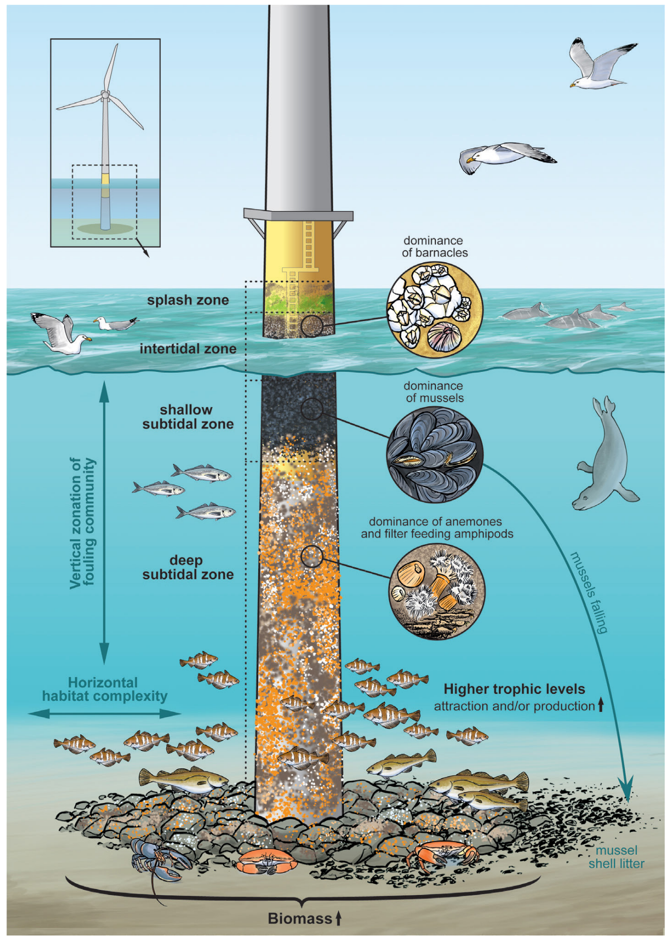


Figure 7: Various types of habitat introduced by the offshore windmill monopile. Image from Degraer et al., (2020) by Hendrik Gheerardyn.

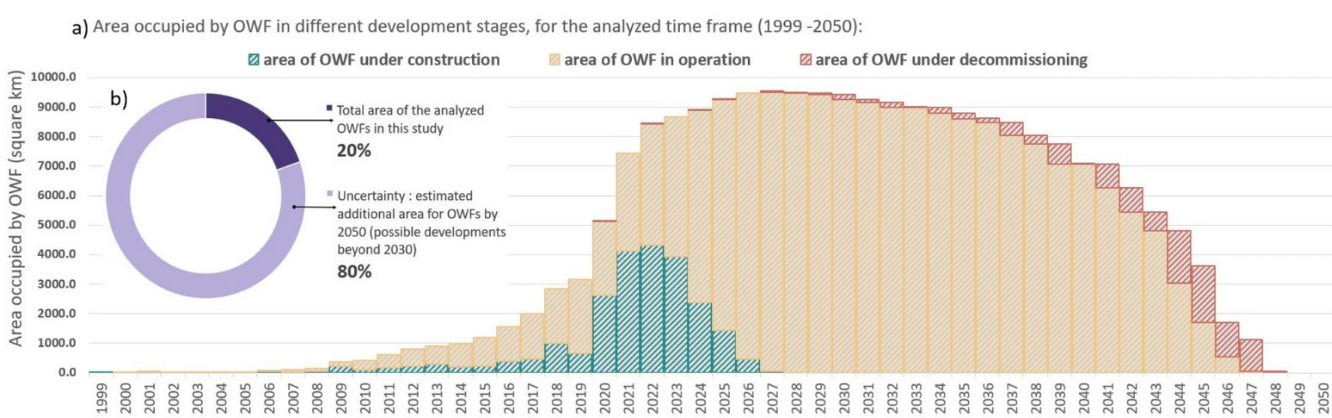


Figure 6: Area of the North Sea basin occupied by offshore windmill farms. The repository is created using already known projects' data, where start date of construction and operation is decided, that is why year 2027 is the last year considered for construction from the known offshore windmill farm plans. Image from Gușatu et al. (2021)).

Different countries apply varied level of fishing restrictions: from no fisheries being allowed in Germany waters to fishing activity restricted only in the safety zone (50m radius from the windmill) in Scotland, in The Netherlands and most countries, bottom trawling in strictly not allowed (SEANSE, 2019) because this would pose danger to hitting the cables and other offshore windmill farm elements on the seabed. In that sense, potential area of protection is of minimum 9577 km^2 (Gușatu et al., 2021) for at least 25-year lifetime of windmill farm construction, operation and decommissioning periods.

1.4 The stakeholders

The key stakeholders of this design project are humans and non-humans: ARK Rewilding Nederland, Ørsted, Flat Oysters, and marine ecosystem.

1. The client: ARK Rewilding Nederland

ARK Rewilding Nederland is an organization working on recovering ecosystems in the Netherlands through rewilding approach, focuses on land and marine ecosystems regeneration as well as education on rewilding itself. With "The North Sea" project, ARK aims to make living nature in the sea robust, varied, and exuberant again. Currently, ARK is searching for effective ways to rewild The North Sea by 'kickstarting' the ecosystem with the key species of flat oyster, blue mussel, horse mussel and other benthic species to start forming biogenic reefs which will positively affect other marine species. One of their goals is to develop structures which could be deployed on a large-scale to the North Seabed with young or adult oysters.

Resources: ARK has expert knowledge in creatin nature restoration strategies, implementing them and monitoring them. ARK also has an extensive network of partners. For example, by working together with Stichting Zeeschelp, they use empty oyster shells, collected from the partner restaurants, as a young oyster growth medium.

Limitations: ARK does not have marine vessels or equipment for large-scale marine restoration operations. It also does not have enough finances to initiate large scale marine ecosystem restoration on their own, they do tend to partner with other companies on these projects.

Needs: ARK needs to find a solution with which oyster restoration would be effective and possible to implement on a large-scale. They want their intervention to be large enough to significantly impact marine ecosystem to a positive direction.

2. Ørsted: offshore windmill farms

Ørsted is an energy company, focused on offshore windmill farms in the North Sea. They want to aid a sustainable energy transition, at the same time exploring how their offshore windmill farms could help in the marine ecosystem regeneration. They partnered up with ARK to develop several projects together to work on offshore restoration projects.

Resources: As a multinational energy company, Ørsted can provide the needed investments to scale up marine restoration projects and expertise related to offshore work. They can also implement or collaborate in marine restoration in multiple offshore windmill farms areas that they operate in. Ørsted could also bring down the operational costs of deploying and maintaining the reef formation solutions as the maintenance of the windmills and the reef formation parts could be done with their vessels.

Limitations: Ørsted does not have the expertise of marine restoration therefore they turn to other organizations to collaborate with in nature restoration projects.

Needs: As a company inversting in nature restoration solutions, Ørsted wants to receive clear results of how much and how well nature has been restored in projects they collaborate in, they also search for marine ecosystem restoration organizations to help them create restoration plans which could be submitted with tenders.

3. The European Flat oyster (Ostrea Edulis)

Having original habitat along the European coast from Norway until Morocco, these oysters were found in The North Sea, Mediterranean and the Black Sea. Highly abundant in The North Sea in 19^{th} and early 20^{th} century, O. Edulis is now functionally extinct in the wild. Currently, they are grown in aquaculture environments by oyster fisheries in Europe, South Africa and USA for food but in relatively low numbers (FAO, 2022).

The native oyster is an important actor for the North Sea ecosystem regeneration, because it is well adapted to the North Sea environment and can form biogenic reefs offshore, in deeper waters as opposed to highly popular blue mussel of pacific oyster species that prefer nearshore, shallower, environments (Christianen et al., 2018; Smaal et al., 2015). The habitat overlap between European flat oyster and non-native Pacific oyster is limited and there are large areas of the North Sea which have remained unoccupied (Christianen et al., 2018).

Resources: Flat oysters can establish well in hard substrate areas; they filter nutrients from the water and grow forming larger 3D structures. These oysters are well adapted to the deeper waters in the North Sea.

Limitations: Currently, there are not enough individuals in the wild to maintain a steady reef growth, so natural population growth is extremely limited. With mostly sandy seabed, young oysters cannot settle well on the seafloor if there is no hard substrate. Also, without protection young oysters are an easy prey for various predators, such as crabs or starfish.

Needs: To grow and thrive, Flat oyster need hard substrate to cling on and grow, juvenile oysters need protection from various predators. This species also need more individuals in the wild to breed and maintain a steady population growth.

4. Marine ecosystem (crabs, lobsters and etc.)

From the rewilding perspective, the goal of this project is to support the marine ecosystem so would become more robust, healthy, and resilient, therefore, this is the main end client. The main goal is not about restoring Flat oyster presence as a species, but to use it as an important catalyst for building biogenic reefs and creating a healthier North Sea ecosystem. Numerous benthic species such as crabs, starfish, various types of fish, algae, seagrass etc need hard substrate to find food and shelter, grow, and breed. Shellfish reef poses an important opportunity to support this need.

Resources: Rich benthic species diversity supports further biogenic reef growth and improves the nutrient cycles throughout the marine ecosystem. A resilient and healthy marine ecosystem can maintain a stable food network bellow the water and provide food for species above the water.

Limitations: without many hard structures in the North Sea, many marine organisms are limited to small spaces around the scour protections, shipwrecks and some of the biogenic reefs. Space is limited, therefore population growth has a lot of challenges and further ecosystem resilience is declining.

Needs: Many benthic species need hard substrate or shellfish reefs to find food, fish need hard substrate and structures to hide from predators, breed and grow.

1.5 Design vision and goal

Vision: “To facilitate the kickstart of biodiverse reef ecosystems in The North Sea“.

Goal: “To create structures which would enhance oyster reef formation and at the same time facilitate other species of marine ecosystem“.

CHAPTER 2:
CONTEXT ANALYSIS

2.1 Methodology

2.2 The sea

2.3 The land meets the sea

2.4 Design requirements

2.5 Current approaches

Deploying young oysters in Voordelta with ARK Rewilding Nederland, Waardenburg Ecology and Stichting Zeeschelp.

Photo credits: Gwenaël Hanon, ARK Rewilding Nederland.

2.1 Methodology

To understand the context of biogenic reef restoration and the environment of the offshore North Sea, background research was done using multiple methods. Firstly, interviews with marine biology and ecology experts from ARK were conducted, main topics and times are summarized in Table 1.

Secondly, a literature review was carried out to find the necessary details about offshore windmill farms and biogenic reef ecosystems, using keywords 'Hollandse Kust (west)', 'shellfish reef restoration', 'Ostrea Edulis, 'European flat oyster', 'biogenic reefs' and cross-references. Used literature comprised scientific articles, governmental, NGO or university research reports, datasheets. Thirdly, two field trips were organized to collect the direct insights in the context, see Table 2.

Table 1: Interviews with marine biology and ecology experts from ARK, highlighting the main topics and time of the interview:

Topics discussed with ARK's experts	When
Requirements for biogenic reef restoration in the North Sea, main approaches, main ecosystem species for reef restoration. Details about European Flat oyster breeding and survival.	14-09-2022
Most common challenges and threats for biogenic reef restoration.	20-09-2022
Context of running offshore marine ecology restoration operations.	28-09-2022
Current approaches and the challenges when implementing them.	4-10-2022
Details about the North Sea offshore marine environment (operations, vessels, technical details and various challenges).	12-10-2022

Table 2: Field trip summary highlighting visited places and main goals of each trip.

Place	Goal	When	With whom
Oyster hatchery 'Stichting Zeeschelp', Kamperland, The Netherlands	To help prepare spat on shell for deployment, gather direct insight about the procedures used to grow Flat Oysters and prepare them for deployment into the Sea, what equipment is used.	19-09-2022	ARK Rewilding Nederland, Waardenburg Ecology, Stichting Zeeschelp
Brouwersdam, Ouddorp, The Netherlands	To help deploy spat on shell in Voordelta, gather direct insight on oyster preparation and deployment operations.	23-09-2022	ARK Rewilding Nederland, Waardenburg Ecology, Stichting Zeeschelp

2.2 The sea

2.2.1 The offshore windmill farm area

The North Sea environment varies in terms of depth and hydrodynamic factors, such as the strength and direction of prevailing currents. For example, in shallower, near-shore parts of the sea, waves can have a large impact on the seabed and sediment dynamics, while in depths of 25-30m offshore, wave impact to the water flow near the seabed is negligible and tidal currents become the most dominant factor. To better understand the environment the designed structures will be used in and reduce the number of variables, context is specified to an area called Hollandse Kust (west) (HKW) (see Figure 8). The area will act as the initial context to understand the primary design requirements, nevertheless, the characteristics described below can be also applied for other offshore locations with a similar depth in the North Sea.

Figure 8: Location of the Hollandse Kust (west). Image from Rijksoverheid (2022).

Sediment dynamics

The sandy seabed is constantly moving according to various wave patterns, which affect deployed structures and oyster reef formation. When structures are placed on the seabed, some parts will highly likely become sedimented and if oysters are covered in sand for prolonged periods of time, they will suffocate and die out. That is why the impact of sediment dynamics was highlighted as one of the most important factors in North Sea reef restoration projects during the expert feedback sessions. The information about Hollandse Kust (west) area is retrieved from Netherlands Enterprise Agency (RVO) (2021) report. The area is located on the Dutch continental shelf with a sandy seabed and has a non-uniform morphology with three types of structures (see Figure 9):

- **Sandbank:** the largest morphological structure, with width varying from 1 to 3 km, up to 6 m height compared to the surrounding depth and wavelengths up to 10 km. Sandbanks migrate relatively slow, they can be considered stationary for the lifetime of the windmill.
- **The Sand Waves** are smaller and move generally faster with wavelength average of 350 m. The wave height varies between 1.5 and 5m. Sand wave migration speed varies: 0.5 – 0.7 m/year, with a median speed of 2.3 m/year.
- **Mega-ripples**: the smallest and fastest migrating structures, with heights generally up to 20 cm (in some cases could reach up to 30cm). Distance between ripple crests is around 10 m. The migration rate is the fastest compared to previous structures, and can reach up to 1 m/h.

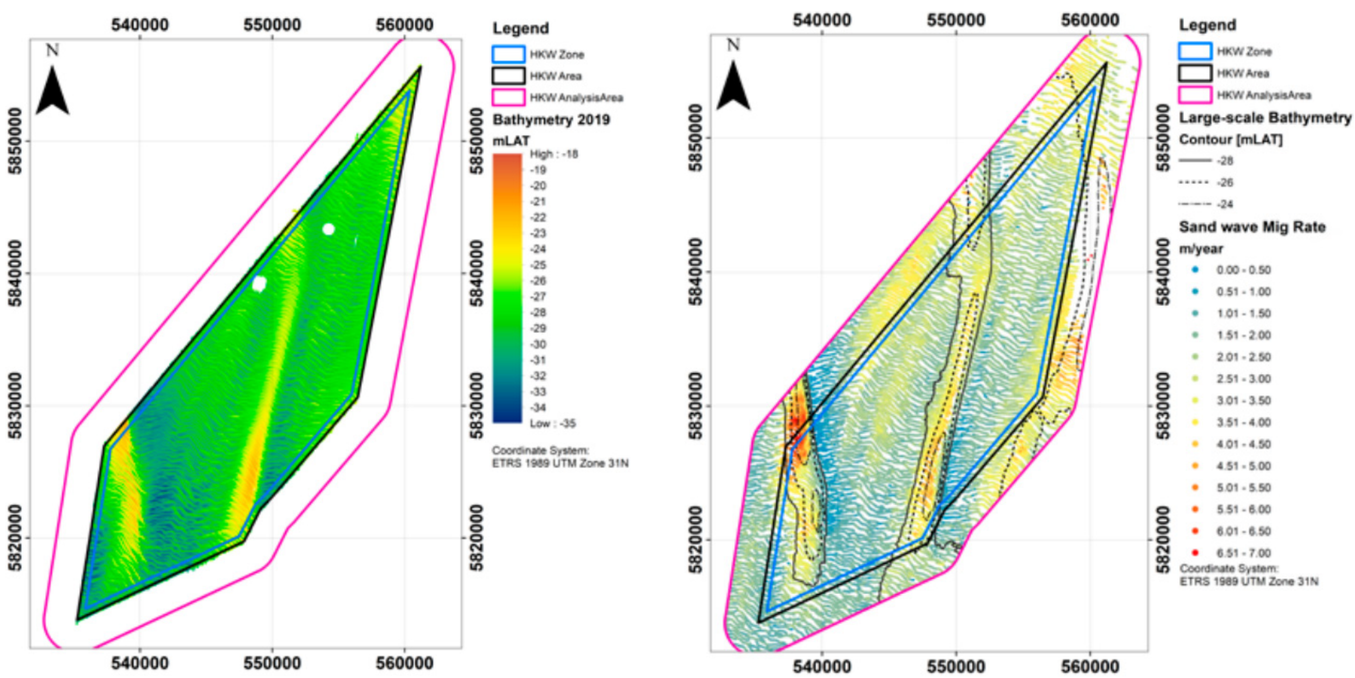
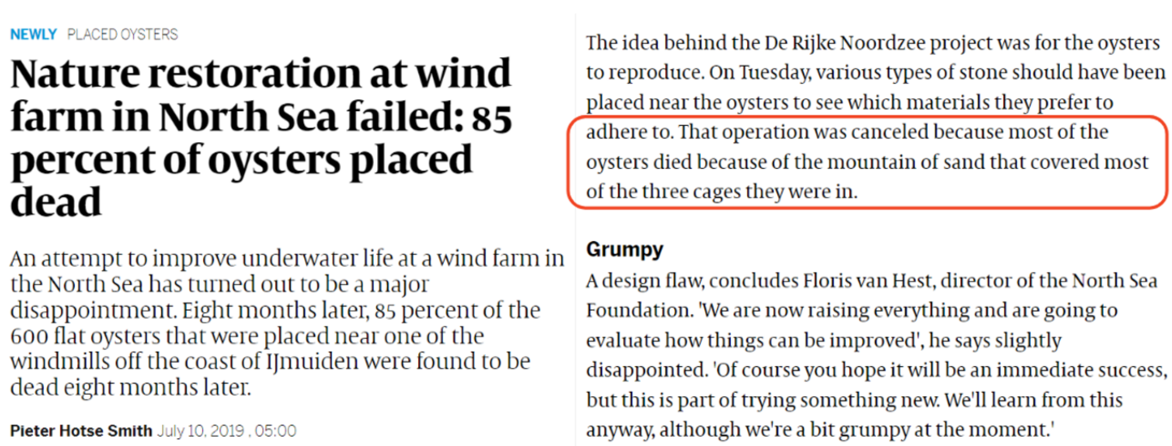


Figure 9: (Left) Sand bed height as measured in 2019, (right) sand wave migration rate. Images from Netherlands Enterprise Agency (2021).

How does this affect design? The sandy seabed is constantly moving according to the different wave patterns, which will affect the reef formation. While sandbanks and sand waves migrate relatively slow, allowing benthic species to outgrow the incoming sedimentation, mega-ripples are moving fast enough to bury structures with oysters bellow the sand and suffocate them. In larger reef structures this sedimentation problem is minimized because the ripples cannot reach far into the reef and only affect the edges, but in the case of oyster deployment in relatively small clusters, sedimentation can have a detrimental effect, see Figure 10. To avoid significant deployed oyster loss, designed structures need to reflect these dynamics.

Design criteria for Flat Oyster survival: the structure should protect oysters from sand mega-ripples of at least 20 cm height.



NEWLY PLACED OYSTERS

Nature restoration at wind farm in North Sea failed: 85 percent of oysters placed dead

An attempt to improve underwater life at a wind farm in the North Sea has turned out to be a major disappointment. Eight months later, 85 percent of the 600 flat oysters that were placed near one of the windmills off the coast of IJmuiden were found to be dead eight months later.

Pieter Hotse Smith July 10, 2019 , 05:00

The idea behind the De Rijke Noordzee project was for the oysters to reproduce. On Tuesday, various types of stone should have been placed near the oysters to see which materials they prefer to adhere to. That operation was canceled because most of the oysters died because of the mountain of sand that covered most of the three cages they were in.

Grumpy

A design flaw, concludes Floris van Hest, director of the North Sea Foundation. 'We are now raising everything and are going to evaluate how things can be improved', he says slightly disappointed. 'Of course you hope it will be an immediate success, but this is part of trying something new. We'll learn from this anyway, although we're a bit grumpy at the moment.'

Figure 10: Excerpt from the news article, illustrating the detrimental effects to the oysters due to sediment dynamics (Smit, 2019).

Currents

Current speed influence is two-fold: it affects the sediment migration speed and direction, and it can affect oyster or deployed structure stability on the sea floor. Two dominant water current directions are impacted by high and low tides, while residual currents have close to negligible impact, see Figure 11.

How does this affect design? If shells with young oysters are deployed freely without securing them, they will be dispersed and carried away from the initial location, making it impossible to retrieve any data and get important insights on restoration project development. Same would also happen with deployed structures if they are too lightweight and/or the geometric shape is unstable (for example – a cylinder would be susceptible to rolling). In addition, mobile structures may also negatively affect the oysters which are sedentary species, and other marine species will not be able to cling on and grow on these mobile structures.

Design criteria for broader ecological success: to ensure location stability, structures should be designed to withstand the sea current speeds of 0.7 m/s from multiple directions, and speeds of 1.2m/s in extreme cases (usually two directions).

Windmill End-of-life

While operating, the windmills offer a hard substrate for benthic species to thrive on while no-fishing zones create safe-heavens for various marine species. But what happens when the offshore windmill farm is decommissioned?

Different end-of-life scenarios affect marine species directly and indirectly. After the expected 25-year lifetime legislation for decommissioning of an offshore windmill farm is not strictly defined and there are two end-of-life (EoL) scenarios: complete or partial removal (Pakenham et al., 2021).

In case of partial removal, the windmill foundation is cut and left to a distance below the seabed (Pakenham et al., 2021) or leaving >25 m draught (Fowler et al., 2019). For a complete removal, all monopile steel foundation needs to be taken out of the seabed and the hole must be filled-in to favour the 'left as found' code. While favouring the material recovery, complete removal has severe negative ecological effects because the ecosystem which surrounds the monopiles is severely disturbed, whereas partial removal maintains the created artificial reef and it preferred from the ecosystem perspective (Pakenham et al., 2021; Fowler et al., 2019).

In case of no-fishing zones, if decommissioning process follows the complete foundation removal EoL scenario, the area would be again opened

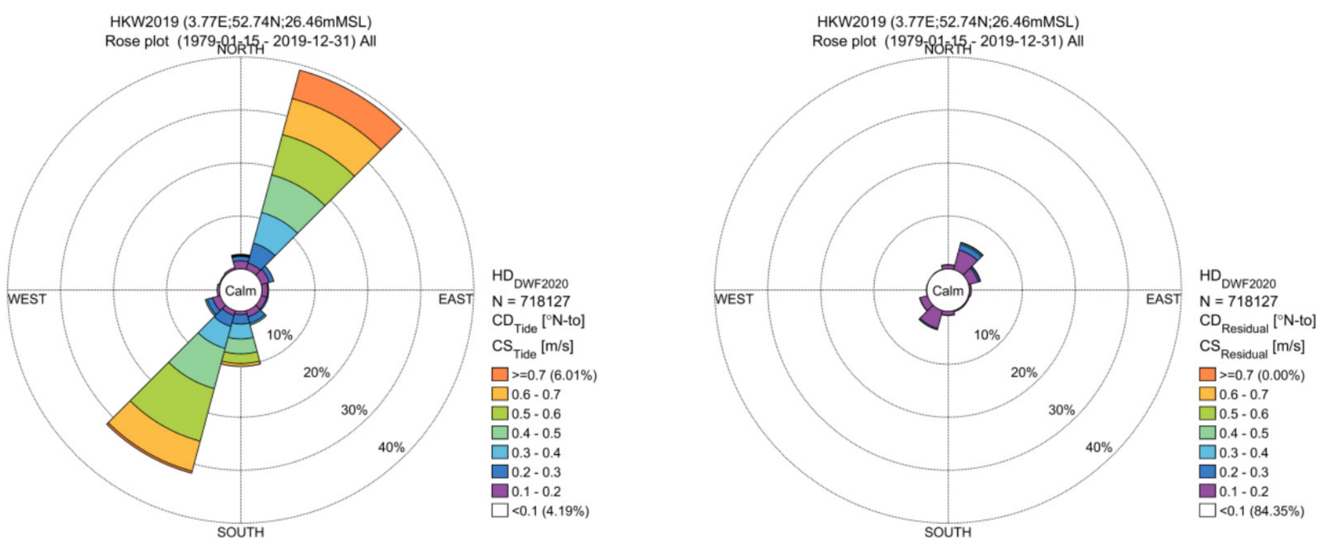


Figure 11: Depth-averaged velocity and current direction and speeds of tidal (left) and residual (right) currents at HKW location (DHI, 2020).

up to fishing activities including bottom trawling (Sommer et al., 2019), and if the partial foundation removal scenario is followed, the area would be protected from fishing practices that disturb the seafloor (Fowler et al., 2019).

How does this affect design? Windmill decommissioning legislation does not have a fixed scenario, and operating windmill structures are highly protected to avoid any damage. Taking this into account, the designed structures need to be self-sustaining and independent from the windmills, in case of any windmill decommissioning scenario the structures will remain intact.

Design requirement: Structures should be structurally independent from the windmills.

2.2.2 Offshore marine ecosystem

The design aims to enhance the biogenic reef formation which is a crucial element for the biodiversity of the North Sea. From biodiversity perspective, structures should improve the habitat conditions for wide variety of marine species even before the natural reef is formed there.

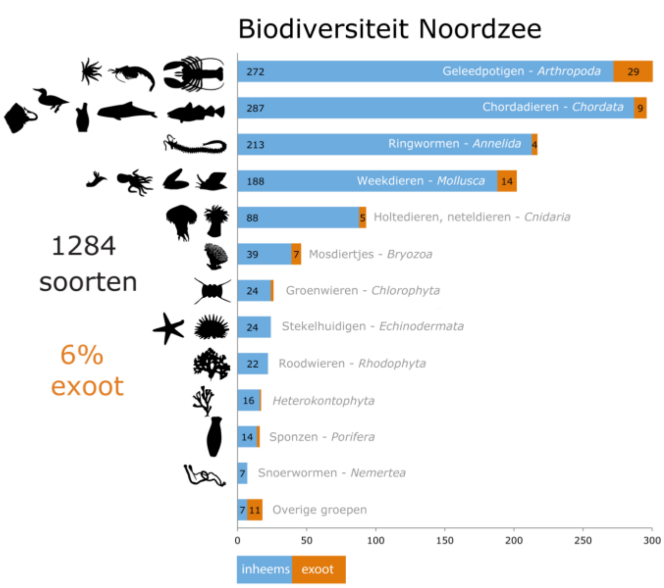


Figure 12: Main categories of the species in the Dutch waters of the North Sea (Bos et al., 2016).

North Sea is rich in life (see Figure 12) with the majority of species consisting of:

- Anthropods (crabs, lobsters, shrimps)
- Chordates (fish, mammals, and sea squirts)
- Annelids (ringed and segmented worms)
- Molluscs (shellfish, squid)
- Coelenterates (anemones, jellyfish)

Because the design context is an offshore environment, the list is narrowed down to the species communities which are building reefs or using the hard substrate in deeper waters (bellow -20 m).

Reef-building species

These species act as an ecosystem engineer by building hard substrate reefs and in that way changing the local morphology and hydrodynamics of the seabed. The list is limited to a few native species, which are adapted to thrive in the depths of the North Sea (Duren et al., 2017):

- Sebellaria: a genus of marine worms which build relatively large structures by gluing up the sand into hard structures (Dubois et al., 2006; Ayata et al., 2009). In Dutch waters these reefs occur rarely due to the disturbance of the seafloor, some hard substrate is required to initiate reef formation (Duren et al., 2017).
- Sand mason worms: can be found in sites ranging from intertidal zone to the depths of 1700 m.

Figure 13: The honeycomb worm formed reef. Image credits: By Júlio Reis - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1105144

- Flat oyster: previously abundant and with extended range along the European coast, over-exploitation, and parasite Bonamia has brought these oysters to extinction in most of the European waters. Currently, flat oyster beds are considered to be one of Europe's most threatened marine habitats (OSPAR Commission, 2008). Flat oysters tend to form beds with three-dimensional structures consisting of living oysters, shells and other species. They prefer calmer, deeper waters as opposed to the popular Japanese Oysters or Blue Mussels which prefer intertidal zones (Duren et al., 2017). More information about Flat Oyster can be found in sub-chapter "2.1.3 Flat oyster".
- Northern horse mussel: mainly found in deeper waters (30 – 60 m), is an arctic - sub-arctic species which prefer colder waters and can be found in the North part of the North Sea.

Species using hard substrate

Currently hard-substrate related species are finding it challenging to disperse due to the lack of hard substrate structures in the North Sea, they use windmill farm foundations and navigation buoys and wrecks. Some of the species include: Benthic species:

- Crabs (hairy hermit crab, edible crab)
- Lobsters (squat lobster species)
- Soft coral species
- Sea anemones
- Sea stars (common starfish)
- Worms
- Bivalves
- Sponges
- Snails (poatched egg shell)
- Cod (Poor Cod, Atlantic Cod)
- The goldsinny wrasse
- The leopard-spotted goby

Habitat complexity is very important for many benthic and epibenthic species because it creates numerous microhabitats with different water current directions and speeds, provides a lot of gaps, holes and cracks to hide, breed, and forage (Duren et al., 2017). Varied habitats are also more productive, resilient and more resistant to invasive species (Alexander et al., 2014). Biodiversity needs diversity: highly complex habitat can cater a wide range of various species needs which is a precondition to biodiverse benthic and epibenthic community (Clare et al., 2015; Kristensen et al., 2015). This is why the loss of habitat complexity and structure simplification is considered as one of the key causes of biodiversity loss (Duren et al., 2017).

Design criteria for broader ecological success: provide structures with surface and structure complexity to cater the needs of benthic and epibenthic species living in hard-substrate habits. Provide gaps, cracks and holes to increase the surface area / volume ratio.

2.2.3 Flat Oyster

Feeding

Oysters filter the water and feed on suspended matter such as phytoplankton, detritus, or inorganic matter. To ensure constant nutrient inflow, adult oyster, depending on its size, filters water at the rate around 1-3 L/h (Water flow bellow 1L h^{-1} oyster^{-1} and above 3L h^{-1} oyster^{-1} will lead to increased oyster mortality) (Maneiro et al., 2020). Phytoplankton is essential nutrient source for oysters to growth, other organic matter, which is undigested concentrated and deposited in turn fuels local food webs (Kamermans et al., 2018). O. Edulis lifecycle has four main stages (see Figure 16) :

1. Reproduction (pelargic) period (6 – 10 days): fertilized eggs develop into larvae with two shells while being contained in the female oyster. Larvae are released after this period into the water (Smaal et al., 2015; Didderen et al., 2019).

2. Recruitment period (10-30 days): free swimming period, takes place in June-August, larvae are growing and looking for a place to settle permanently. Settlement happens once

larvae detects a suitable location (Smaal et al., 2015). It was discovered that oyster larvae pick up chemical and audible cues (McAfee et al., 2022) to decide where to settle, oyster shells or other calcific material with similar chemical composition is preferred by the larvae (Colsoul et al., 2020) as well as presence of biofilm (Rodriguez-Perez et al., 2019). Dispersal distance is rather small compared or other bivalves: up to 10 km (Berghahn & Ruth, 2005).

3. Survival period (0 – 2 years): once the larvae glue themselves permanently onto the hard substrate they become Spat and grow quite fast in initial stages (Figure 14 and Figure 15). In reef restoration projects, Spat of 1-2 months old is usually deployed to the sea, but still needs protection from predation. By the time spat is 1 year (shell size is around 30mm (Robert et al., 1991)) shell is already much harder making the predation harder, and by the time spat is 2 years, the shell is hard enough to offer effective protection and is called juvenile oyster.

Figure 14: One-month old spat on shell. Picture taken in the oyster hatchery.

Figure 15: Two-month old spat on shell. Picture taken in the oyster hatchery.

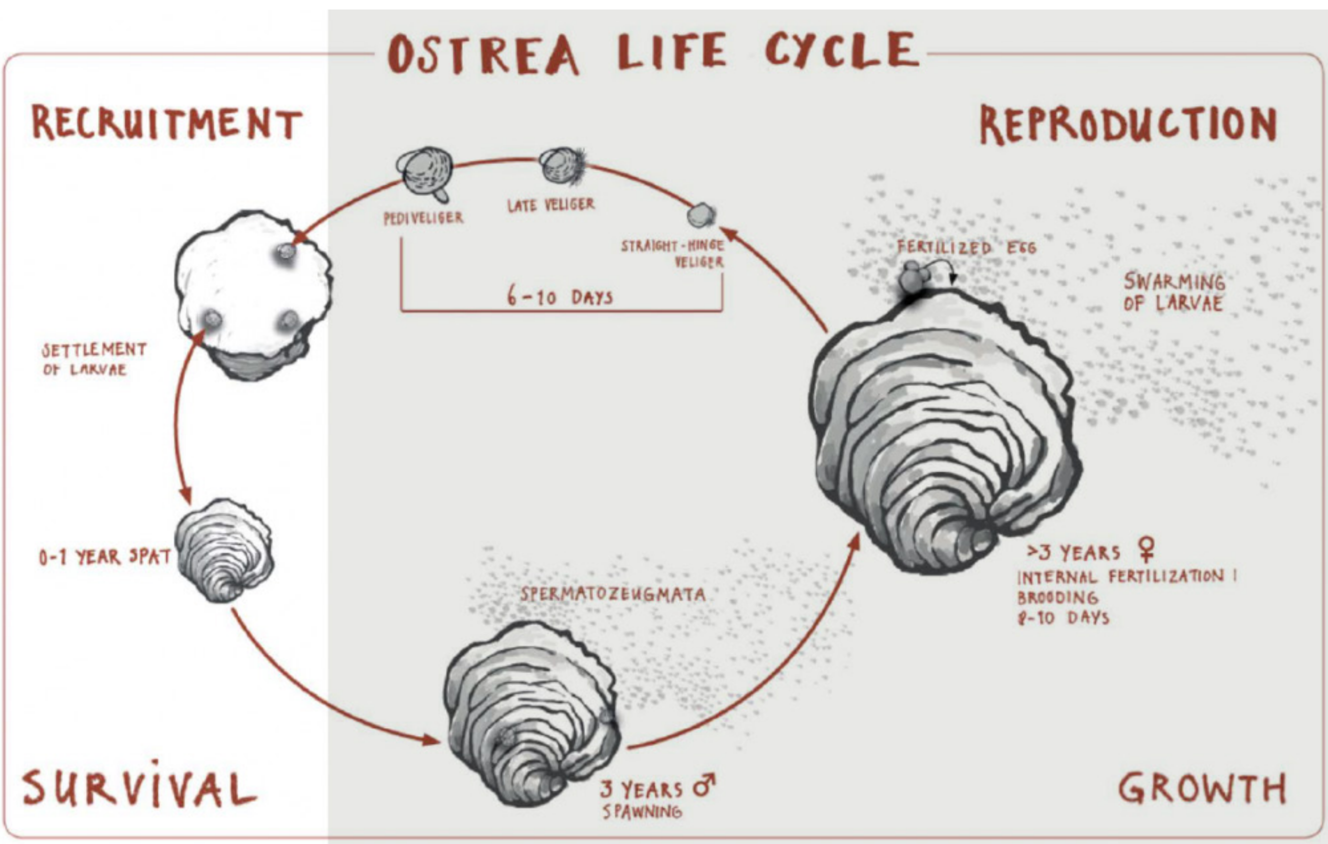


Figure 16: Ostrea Edulis life cycle. Image credits: Hein Sas (2019).

4. Growth period: Juvenile oysters reach adulthood at 3 years old. All juvenile oysters initially are male but once old enough (3-4 years), turn to female (Smaal et al., 2015). This is important to note, when reintroducing Flat Oyster colonies into uncolonized area, oysters should be deployed 3 years in a row to ensure a mix of genders and successful reproduction.

Predation

O. Edulis, especially the young oysters, are generally predated by various types of starfish (for example, the Common Starfish) and crabs (for example, edible crab) (Didderen et al., 2020). When oysters are young their shell is soft enough for these predators to crack or open them up, but in their adult stage, the predation is minimized due to stronger shell formation.

Restoration

Introducing flat oyster spat can also help boost the chances that the shellfish reef can be kickstarted, because minimum of 60000 oysters is required to form a self-sustaining shellfish reef. 7 oysters/m^2 is considered a reef.

Insights gained from research and expert feedback about the Flat oyster are systemized in Figure 17.

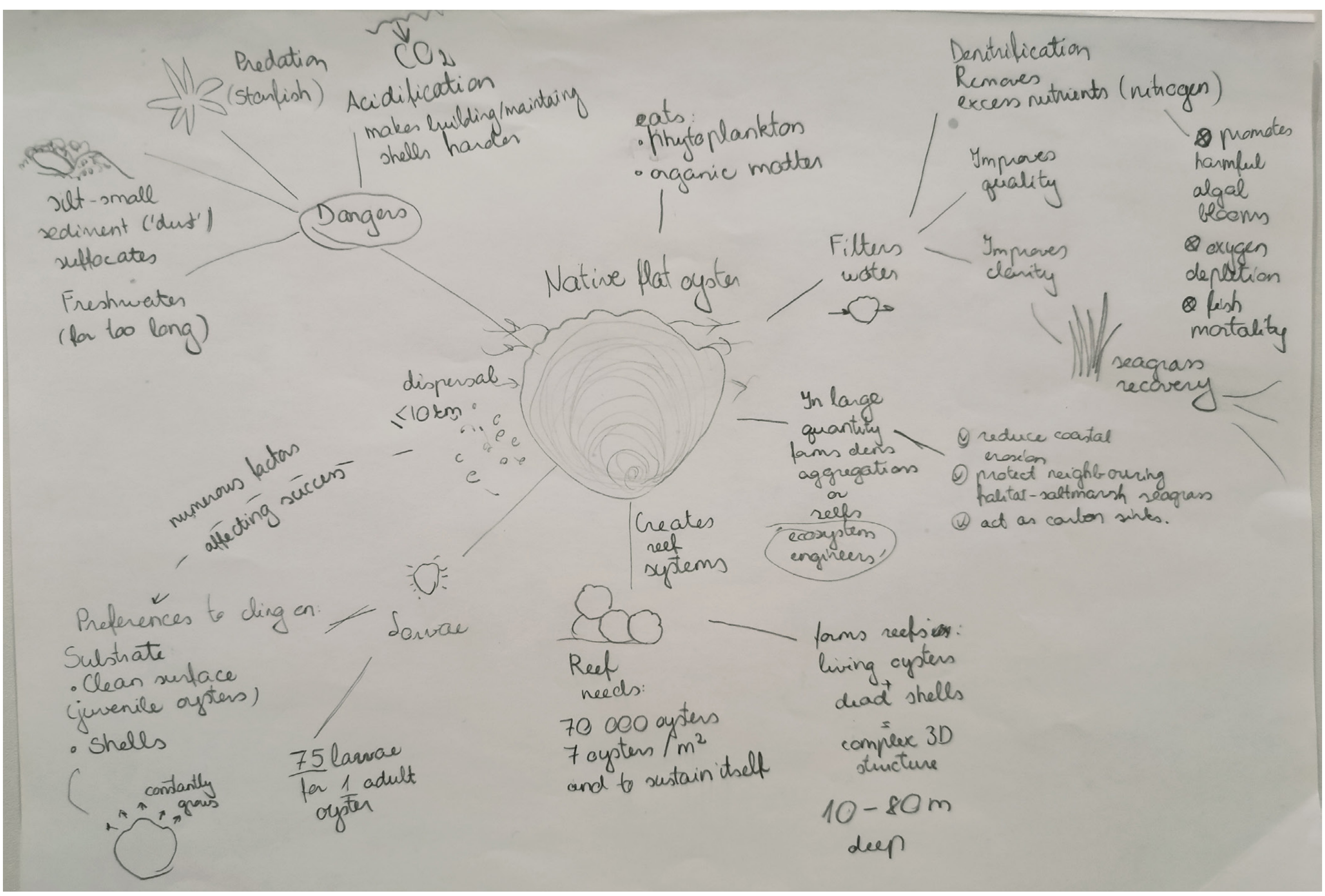


Figure 17: Native Flat Oyster - main insights and effects in the ecosystem.

How does this affect design? Flat oyster development analysis provides several design criteria:

Design criteria for Flat Oyster survival: structures should allow constant and effective waterflow for the oysters.

Design criteria for Handling & deployment: deployed structures should be possible to locate, to deploy young oysters several years in a row.

Design criteria for Flat Oyster survival: structures should be designed to protect juvenile oysters from predation (mainly form crabs and starfish) until they are 1-2 years old, but also provide enough space for them to grow.

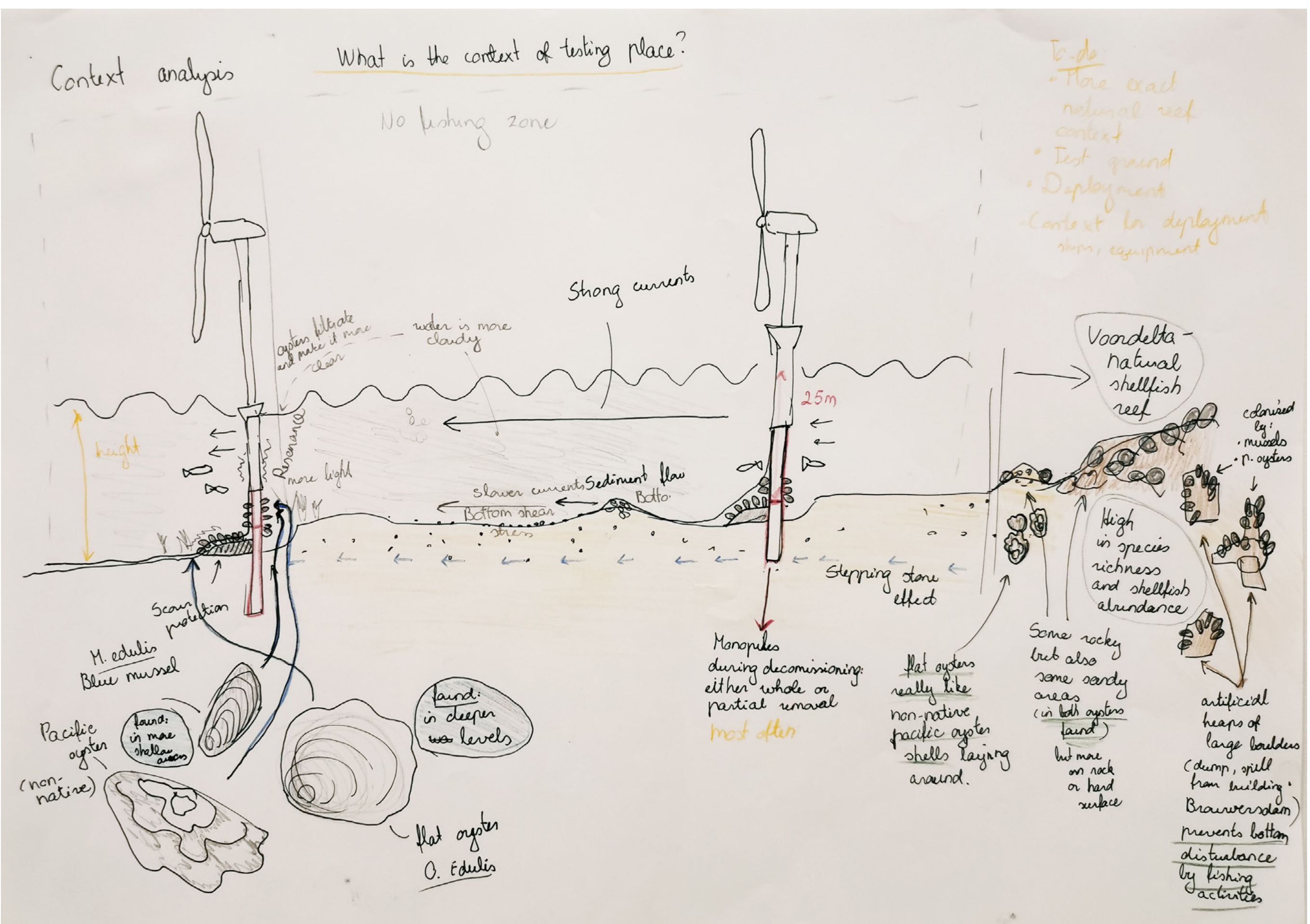


Figure 18: Current offshore windmill farm environment compared to the natural reef in Voordelta.

2.3 The land meets the sea

To field trips have been planned. Firstly, Oyster hatchery “Stichting Zeeschelp” was visited to get some direct insights and experience in handling spat on shell. Secondly, spat on shell deployment in Brouwersdam was organized where insights about these operations were gathered.

2.3.1 Oyster hatchery

Since recruiting wild spat from the North sea is not feasible, native oyster restoration projects turn to oyster hatcheries for the source of young healthy oysters. To better understand the details surrounding this stage of the project, a partner oyster hatchery Stichting Zeeschelp was visited. Everything starts with algae: multiple species of algae are cultivated in the greenhouse (see Figure 20) and shellfish nutrition mix is adapted to their growth phase with varied algae mixes for larvae, spat and adult oysters. Different nutrition mixes are transported via tubes straight to the tanks with oysters.

After the initial stages of growth, oyster larvae are introduced to the main tanks where they are left for 1 to 2 months to settle on the hard surface and grow (Figure 21). The tanks are cilindrical to ensure even water flow and assembled in a limited space. The hard substrate for larvae was loose empty oyster shell in boxes (Figure 22). The boxes needed to be put and taken out of the tanks by hand, due limited space.

When spat is one or two months old they are old enough to be deployed, but their shells are still very delicate and can break easily when being handled in a rough way. Usually, empty shells are put into the dedicated structures or installations before the spat settlement to avoid moving fragile spat too much. In this case several different deployment

Figure 20: Different species of algae are grown in the facility’s greenhouse.

Figure 19: A view from Stichting Zeeschelp.

Figure 21: Water tanks where spat is kept to settle on hard substrate.

methods were planned, therefore, the shells were loose when they were put into the tanks with oyster larvae. One of the main tasks for the visit was to prepare the spat on shell for deployment to the North Sea: refill the spat on shell from loose boxes to the oyster nets (Figure 23).

At least one person was needed to transport the boxes with spat from the tanks to the refilling area, minimum 3 people were needed to effectively refill the spat from boxes to oyster nets (Figure 23). The task was both time and human labour intensive. Due to rough handling, some spat has fallen on the ground during the refiling procedure. Also, spat which settled on empty shell edges was more prone to being crushed or knocked off.

How does this affect design? Overall, the process has highlighted the importance of incorporating the structures for oyster settlement into the hatchery facility. This approach would reduce the time and workforce needed for spat preparation and lower spat mortality rate. In addition, current facility has limited space and spat is being handled by hand, so the structures should be lightweight enough to be handled by 1 or 2 people.

Design criteria for Handling & deployment: structures should be integrated into the hatchery during the time when spat is in the settlement stage.

Design criteria for Handling & deployment: structures should be lightweight enough to be handled by 1 or 2 people.

Figure 23: Refiling spat on shell from boxes to oyster nets (orange).

Figure 22: Right - crates with spat on shell taken out of the water tanks. Left - spat has settled on shell in all directions as well as on the crate itself.

2.3.2 Deployment at Brouwersdam

After spat preparation the deployment took place in Brouwersdam, where three different deployment techniques were tried out: steel table (Figure 24), nets raised on beams (Figure 25) and loose oyster shell (Figure 26) around the installation. Two steel tables were used as a foundation to raise the oyster nets from the bottom ~30 cm. Both tables needed to be secured onto the seafloor before deploying the oysters. For securing the table and the oyster nets two small boats were used with two divers constantly working close to the seafloor while 2 to 3 people were working on the boat.

Overall, the sea was relatively calm but the work on a small boat was still challenging due to a constant rocking. Around 15 m^2 of area was covered with oyster nets and loose oysters for research and testing purpose. The process was time and labour intensive due to several reasons:

1. The structures had to be fixated onto the seafloor in a specific position, therefore, divers were needed to ensure that upright stable position. Preparations for diving and installation took a lot of time.

2. due to limited space on boats (Figure 27), three trips were needed to the place and back to the. Securing the boat close to the installation with increasing wind was also challenging and time consuming.

3. The installation was done near-shore in shallow waters, where seabed is frequently disturbed by larger waves and storms, so securing the structures needed more effort.

Figure 24: Steel table ready to be deployed to the determined area. Table will be used as the basis to raise the oyster nets from the bottom.

Figure 26: Loose oyster shell with spat to be dispersed. around the installations.

Figure 25: Oyster nets with beams raising them from the bottom.

Figure 27: Boats from Bureau Waardenburg and Stichting Zeeschelp.

How does this affect design? While there are a few discrepancies between the design context and the context of this deployment, several insights could be highlighted:

- Working on deck offshore is a harsh environment and preparation work on deck should be minimized or streamlined as much as possible.
- If deployment requires divers to check or build the structure, the design is deemed to never reach large scale projects, due to the sheer amount of time and labour that will be needed for successful deployment.

Design criteria for Handling & deployment: structures should require minimal human care to fall to the right position on the seabed and secure temselves.

2.3.3 Overview of the main stages, processes and interactions – the system map.

Insights and knowledge about current operations needed for oyster reef restoration project were collected during both field trips. To get a better overview of the current stages, processes and interactions, a system map was created as a first part of the Whole Systems Mapping method (Figure 28). The map highlights the main stages, such as collecting empty oyster shells, using these shells in oyster hatchery, preparing young oysters for deployment and deploying them. In addition, important interactions with biotic and abiotic factors are highlighted as well. For example, once the structure is deployed onto the seabed, it affects and is affected by the environmental factors, such as water flow and sediment flow. Various types of biota interact with the structures as well: juvenile fish may gather, new oysters start growing, predators may come for flat oysters. The system map provided a good overview of these processes for further design process.

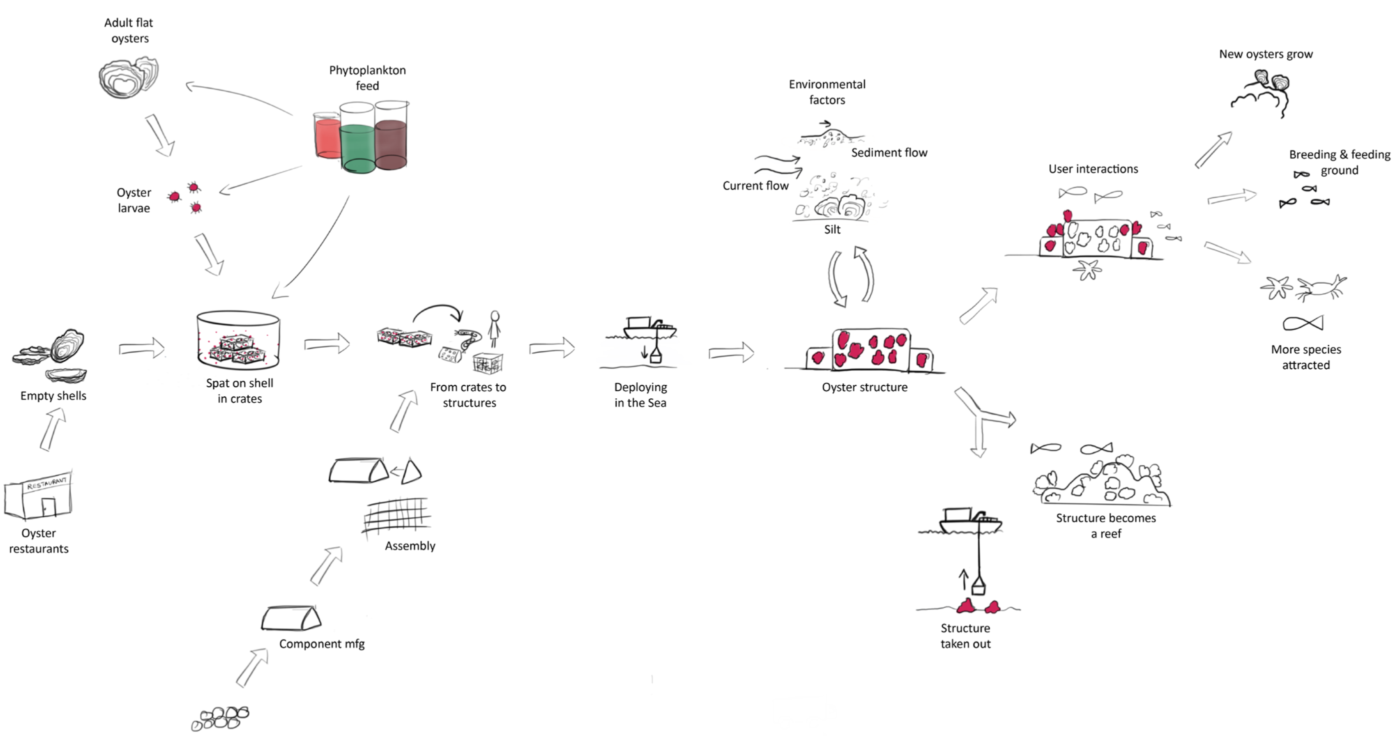


Figure 28: The current system map.

2.4 Design requirements

Inputs from design exploration were translated into the design requirements. Factors which related to structures being independent from the windmills and non-toxic/non-polluting to the marine ecosystem were non-negotiable and had to be satisfied and were categorized as design requirements (see Table 3), if the design did not satisfy both of them – it was classified as not viable for this project. Many factors, which did not have such strict viability boundaries, especially the ecological factors which were not possible to calculate or predict with high precision at the time of the project, were classified as design criteria (see Table 4). The design criteria were grouped in 4 categories and used to evaluate currently used approaches, conceptual ideas in Chapter 4 and final design in Chapter 5.

The design criteria (Table 4) were grouped into 4 categories: Flat Oyster survival; Scalability; Broader ecological success; Handling and deployment. Some factors have more importance in determining whether the design is effective in biogenic reef restoration. For example, it does not matter how lightweight the structures are, if they do not help oysters to survive, or the design is not scalable. Therefore, the criteria were given different weights, which determined their importance to the design. In this way, current approaches, design ideas and final design could be evaluated more accurately.

Table 3: Design requirements for this project with explanation.

Requirement	Explanation
1. Structures should be independent of the windmills.	Windmill farms have several decommissioning scenarios of which the majority would inflict severe damage if the reef structures were built close to the windmill. In addition, due to windmill security, most of the offshore windmill companies want to avoid attaching external structures to the windmills.
2. Structures should not emit toxins to the marine environment or pollute the Sea with nondegradable materials.	When structures are deployed and left to decay on the seabed, marine life will directly interact with them. Therefore, structures should not harm oysters or other marine organisms by releasing toxic elements or by polluting the waters with non-degradable parts which could end up harming the marine life.

Table 4: Design criteria sorted in 4 categories, each criterion importance expressed in weight with argumentation.

Flat Oyster survival: these ecosystem engineers are one of the few reef building species in the deeper areas of the North Sea. With limited supply of suitable juvenile flat oysters, high mortality can greatly impact the restoration project viability.		
Criterion	Weight	Explanation
1. The structure should protect oysters from sedimentation, specifically from mega-ripples of at least 20 cm height.	5	If oysters get sedimented by sand or silt too much and for too long, they will suffocate and die out. This criterion has a direct effect to oyster survivability and project viability. Maximum importance – weight 5 is given.
2. Structures should be designed to protect juvenile oysters from predation (crabs and starfish) until they are 1-2 years old, but also provide enough space for them to grow later on.	5	If most of the deployed young oysters get predated upon, there will be no or not enough adult oysters to make a self-sustaining oyster reef. Direct effect to oyster survivability and project viability. Maximum importance – weight 5 is given.
3. Structures should allow constant and effective waterflow for the oysters to ensure nutrition.	5	Oysters are filter feeders and, if they do not get enough nutrients with the suitable waterflow, they will die out. Direct effect to oyster survivability and project viability. Various living organisms will start growing on structure, openings for flow should be large enough to prevent clogging. Maximum importance – weight 5 is given.

Table 4: Design criteria sorted in 4 categories, each criterion importance expressed in weight with argumentation.

Scalability: to do an effective intervention in the marine ecosystem, large amounts of live oysters should be deployed, around 15 m3 of spat on shell to produce a self-sufficient oyster reef with 60000 adult oysters. If design is not scalable, introducing large number of these structures will not be possible and the ecological effect will be negligible.		
Criterion	Weight	Explanation
4. Structures should be low in price for production, assembly, and deployment.	5	If structures are expensive to produce, assemble or deploy there might be not enough of financial resources to produce enough of them to have a significant positive ecological effect. Direct effect to project viability. Maximum importance – weight 5 is given.
5. It should be possible to deploy high volumes of oysters in short amount of time.	5	Time spent in offshore marine operation can be very expensive due to the high vessel rental costs, ship crew and expert salaries. If the design cannot be deployed in a time-efficient way, it will drastically increase the deployment costs. Direct effect to project viability. Maximum importance – weight 5 is given.
Broader ecological success: healthy biogenic reef includes numerous marine species which are essential to a healthy marine ecosystem. To reinforce the positive impact to the marine ecosystem, it should be considered how this wide variety or marine species can be positively affected by the designed structures.		
Criterion	Weight	Explanation
6. Structures should be designed to withstand the sea current speeds of 0.7 m/s from multiple directions, and speeds of 1.2m/s in extreme cases (usually two directions) to ensure location stability.	4	Many benthic species need hard and stable substrate to cling on and grow. If structures are unstable, tilt or dislocate often, species will not be able to grow on them effectively. Flat oysters may not suffer directly from this, but changed position may increase sedimentation or predation, which will have negative effect on them. Mobile structures will be hard to locate and monitor, reducing the possibility to derive intervention results. This criterion has medium indirect effect to project viability. High importance – weight 4 is given.
7. Provide structures with surface and structure complexity to cater the needs of benthic and epibenthic species living in hard-substrate habits. Provide gaps, cracks, and holes to increase the surface area / volume ratio.	2	Introducing gradient conditions (varied waterflow, different types of substrates) can have positive effects on marine biodiversity. Introducing these additional gradients is a nice-to-have, because flat oyster shells will already provide a suitable environment for a wide variety of marine species. This criterion has indirect effect to marine biodiversity. Low importance – weight 2 is given.
Handling and deployment: Designed structures may improve or hamper the efficiency of oyster handling operations from the hatchery up until deployment to the seafloor. This directly affects the operational costs, hence, scalability of the design.		
Criterion	Weight	Explanation
8. Structures should require minimal human care to fall to the right position on the seabed and secure themselves.	4	If successful structure deployment requires a lot of human time and effort (for example, diving), the deployment time costs increase which hamper intervention scalability. This criterion has direct effect to scalability. High importance – weight 4 is given.
9. Structures (or pre-assembled parts) should be lightweight enough to be handled by 1 or 2 people.	2	Several operations in the system (spat preparation for transportation or deployment) usually incorporate manual work. If heavy assembly can be divided into more lightweight parts which can be handled manually, it can be counted as lightweight. If structures (or their parts) are too heavy to lift, additional equipment will need to fit into the hatchery and a vessel, or the task will be divided into several manual operations. This criterion has an indirect effect on deployment time. Low importance – weight 2 is given.

Table 4: Design criteria sorted in 4 categories, each criterion importance expressed in weight with argumentation.

10. Structures should be integrated into the hatchery.	3	If structures are integrated into the hatchery pools, spat will settle on them directly. Having spat already in the structure will reduce the times shells will be handled roughly, thus, reducing spat mortality. Direct effect on oyster mortality. Medium importance – weight 3 is given.
11. It should be possible to locate the oyster structures.	2	Possibility to locate plays an important role after first deployment operations. To get a self-sufficient population, oysters should be deployed at the same place 3 years in a row and it should be possible to locate the structures for monitoring reasons. Small and mobile structures are hard to locate. If they are larger and do not move with currents, they are easier to locate. Low importance because partially solved by criterion 6 – weight 2 is given.
12. There should be a no need to retrieve the structures once they are deployed.	4	If structures need to be retrieved due to their material composition (not naturally occurring, non-degradable), another expensive offshore operation would be needed, which would double the operational costs and severely hamper the viability of the restoration project. High importance – weight 4 is given.

2.5 Current approaches

Multiple approaches to oyster reef regeneration are being tested out around the World, with some being highly successful in one place and completely ineffective in another. To better understand the main strengths and weaknesses of these approaches, interview with an expert from ARK was arranged, after which they were evaluated using the matrix (Figure 29). Current solution evaluations can be found in Figure 30, detailed solution evaluation can be found after.

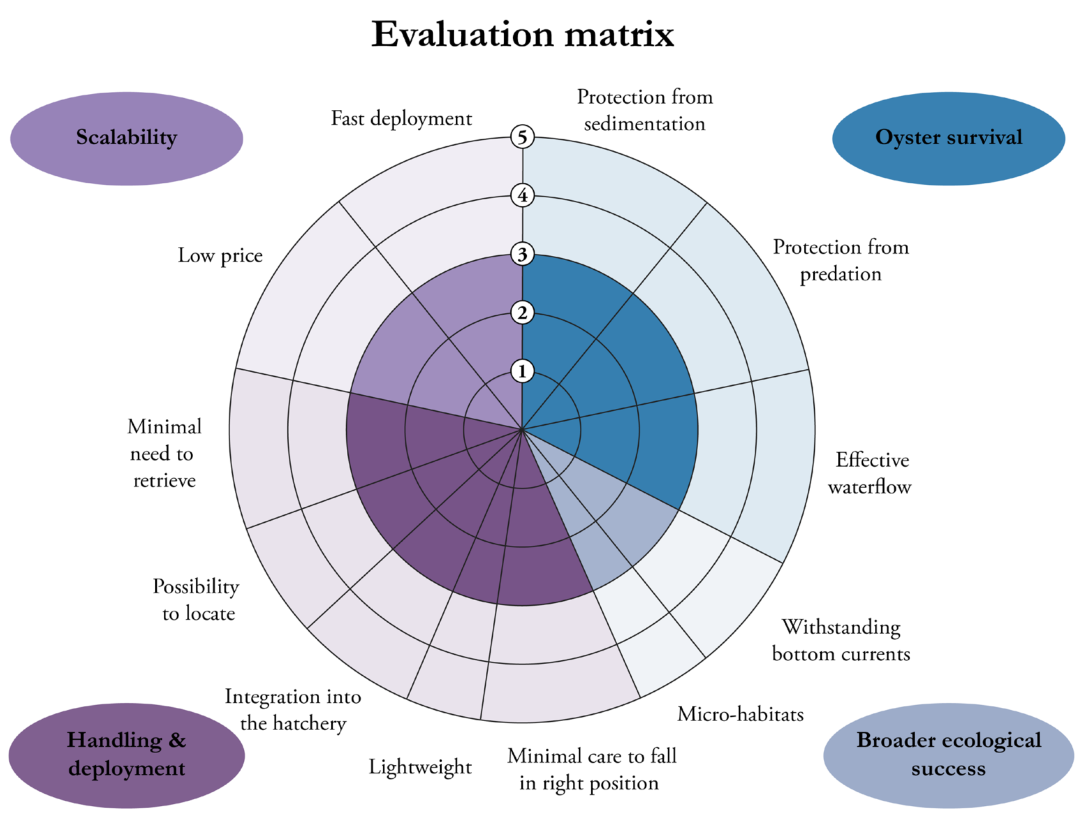


Figure 29: Evaluation matrix reflecting the design criteria and their weights. Design is evaluated according to each criteria: 1 – Not accomplished, 2 – Partially accomplished, 3 - Average, 4 - Mostly accomplished, 5 - Fully accomplished.

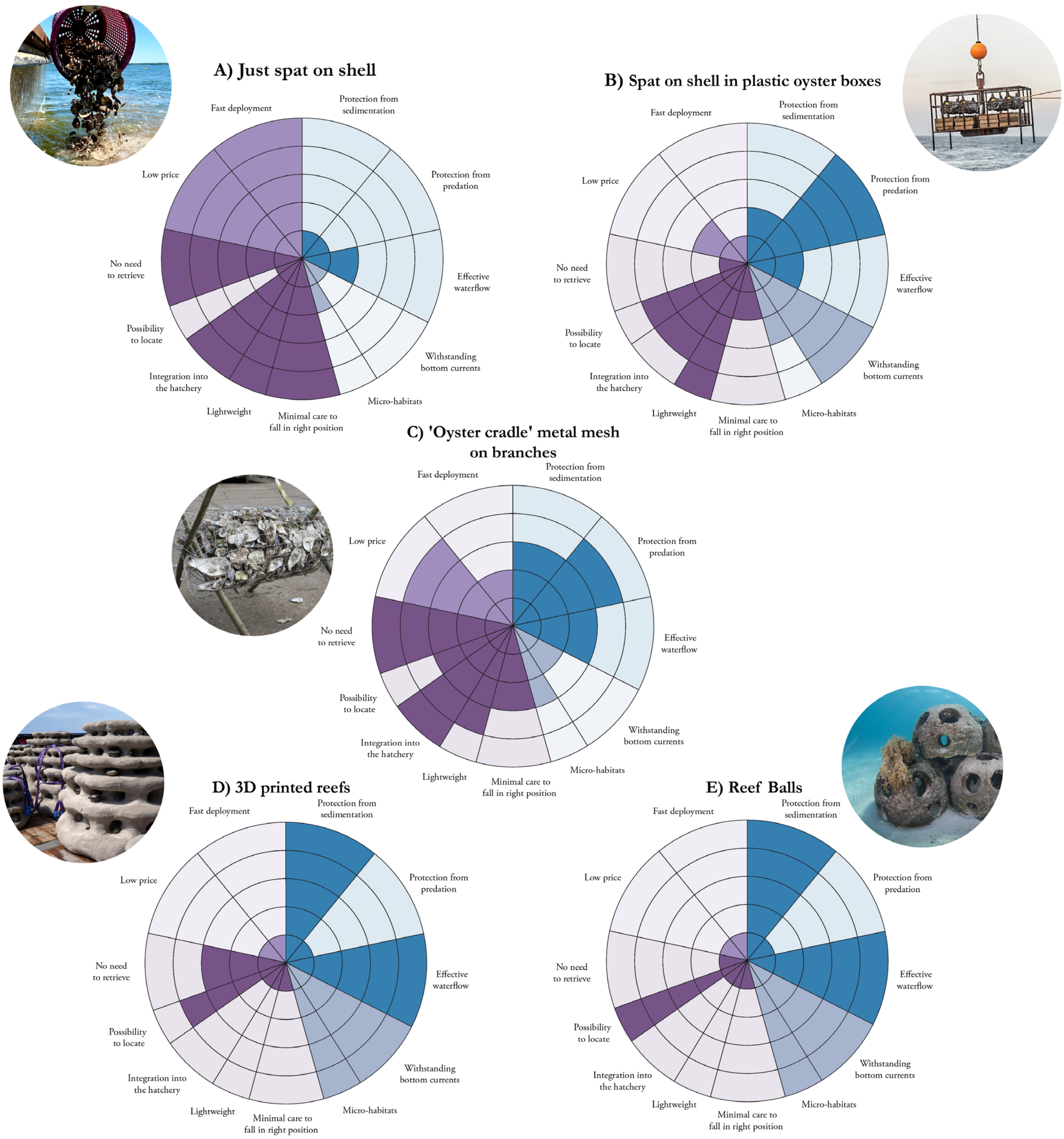


Figure 30: Current solutions evaluated with the matrix. A) - just throwing spat on shell into the water, B) - Spat on shell in plastic oyster boxes in metal frame, C) - 'Oyster cradles' with branches, D) - 3D printed reefs, E) Reef balls.

A) Just throwing adult oysters or spat on shell overboard (Figure 30 – A). Spat on shell can be packed into large containers on a ship and just thrown out into the sea. With no additional materials required, deployment can be easily streamlined to large deployment scale. This approach is proven to work in other parts of the World where empty shells and spat on shell is deployed in massive scales (NOAA, 2021; Bruce et al., 2021), but due to limited supply of Flat Oysters and current legal restrictions in the Dutch maritime zone (deploying large amount of hard substrate such as rock is not allowed), this approach has limited effectiveness in the Dutch waters. When it comes to oyster survival and broader ecological success, this approach underperforms extensively. Separate oysters will drift away and get lost with no possibility to monitor their growth and intervention success. More detailed evaluation is in Table 5.

Table 5: Solution A evaluation per criteria and explanation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	1	Once the loose young oysters are deployed on the seabed, they are not protected from predators, such as crabs or starfish.
2. Protection from predation	1	Not raised from the seafloor, , each shell can get sedimented very quickly.
3. Effective waterflow	2	If the shell gets sedimented, it will be blocked from the waterflow as well.
4. Low price	5	No additional materials required, except spat on shell. Easy deployment procedure without additional equipment.
5. Fast deployment	5	Easy and fast deployment method – just throwing out loads of spat on shell into the water.
6. Withstanding bottom currents	3	Lightweight shells will drift away easily but may become more stable once more shells are clustered together or get sedimented.
7. Micro-habitats	3	Many shells may create some gradient conditions for other species.
8. Minimal care to fall to the right position	5	Shells are just thrown out into the water.
9. Lightweight	5	Shells are lightweight and can be handled by people or machines.
10. Integration into the hatchery	5	Shells are most easily integrated into the hatchery.
11. Possibility to locate	1	Almost impossible to locate because shells drift away easily.
12. Minimal need to retrieve	5	No need (and no possibility) to retrieve because shells are naturally occurring in the sea.

B) Spat on shell or adult oysters in enclosed plastic cages on a metal frame (Figure 30 – B). Polypropylene oyster baskets attached to the steel frame. Incorporating a non-degradable plastic already introduces the requirement to retrieve these structures after the legal period has ended. Oyster basket holes are too small, they will get blocked by algal growth and sand, which will eventually block the waterflow and suffocate the oyster inside. More detailed evaluation can be found in Table 6.

Table 6: Solution B evaluation per criteria and explanation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	2	Oysters are raised from the seafloor, but oyster basket holes are very small and susceptible to getting blocked by sand quickly.
2. Protection from predation	5	Oyster baskets have small holes which will not allow crabs or starfish to reach young oysters.
3. Effective waterflow	2	Small oyster basket holes can get sedimented and overgrown by algae quickly which will block the waterflow.
4. Low price	3	Mostly standard parts, spot welded steel frame is the most expensive part.
5. Fast deployment	1	Deployment process is very slow, because crane is used for deployment. Additional safety protocols slow the process further.

6. Withstanding bottom currents	5	Structures are heavy and will withstand high waterflow. Legs can dig into the sand and stabilize the structure further.
7. Micro-habitats	3	Introduces some material and waterflow variety to the marine environment. Some marine animals may end up trapped inside the oyster baskets.
8. Minimal care to fall to the right position	2	For each structure the crane must be used to put it in the upright position on the seafloor.
9. Lightweight	5	Baskets with oysters are lightweight, can be easily carried and assembled to the steel frame.
10. Integration into the hatchery	4	Baskets with oysters can be easily integrated into the hatchery. However, a lot of spat might settle on the outside basket walls.
11. Possibility to locate	4	Once deployed, structures will not move and can be easily located.
12. Minimal need to retrieve	1	Obligatory to retrieve because oyster baskets are made of polypropylene which is not biodegradable and can pollute the sea.

C) 'Oyster cradle' metal mesh on branches (Figure 30 – C). Structures are made of naturally occurring or biodegradable materials: oyster shells, steel mesh and willow branches so they can be left on the seabed to degrade without needing to retrieve them. Solution offers an effective protection from predation, but the assembly might not be strong enough to withstand high waterflow, with oysters ending up on the seafloor. Deployment is time consuming and labour-intensive, thus inhibiting scalability possibilities. More detailed evaluation can be found in Table 7.

Table 7: Solution C evaluation per criteria and explanation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	3	Oysters are lifted from the seafloor, but some assemblies are not strong enough and the oyster bag can fall directly on the seabed.
2. Protection from predation	4	Many oyster shells are packed together, making it harder from predators to reach young oysters
3. Effective waterflow	3	If oyster cradle falls on the seafloor and get sedimented, the effective waterflow is reduced as well.
4. Low price	4	Relatively low price due to materials which are not expensive: oyster shells, steel mesh and willow branches.
5. Fast deployment	2	Deployment process is slow and labour-intensive: slow unit assembly, each unit needs to be deployed separately.
6. Withstanding bottom currents	2	According to experts from ARK, the structures deployed in the nearshore were not stable enough to withstand the high waterflow and ended up being severely damaged after the storm. (Note: nearshore water currents can get much stronger than in the deeper levels of the sea.)
7. Micro-habitats	3	Packed oyster shells can offer a wide variety of gaps for local biota to live in. Some material and waterflow variety.
8. Minimal care to fall to the right position	3	Each structure is manually deployed (thrown overboard) to ensure that it falls in proper position.
9. Lightweight	4	Packed shells may be heavier but still can be carried by 1 or 2 persons.
10. Integration into the hatchery	5	Oyster cradles are relatively small, can be easily integrated into the hatchery. However, if galvanized steel mesh is used, spat on shell will not settle in these cradles.
11. Possibility to locate	3	Structures are small and can be washed away in strong storm events. This makes them harder to locate.
12. Minimal need to retrieve	5	Made of naturally occurring (oyster shell, willow branches) or biodegradable materials (steel) that can be left to degrade.

D) 3D printed reefs (Figure 30 – D). 3D printed from sandstone, high surface complexity introduces numerous micro-habitats for various species. However, it is impossible to deploy a high number of oysters vwith these structures, because each oyster has to be glued to the structure manually. Current approach is to glue oysters with epoxy, but this will pollute the sea with a non-degradable material. Further, structures offer no protection from predation because they are open and easily accessible for crabs or starfish, hence the survival is going to be very low. Due to the weight and manufacturing approach, the price can go up to 1500 euros per unit, and the whole deployment process is extremely slow, making the whole solution almost impossible to scale up. More detailed evaluation can be found in Table 8.

Table 8: Solution D evaluation per criteria and explanation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	5	Structures can raise the oysters high enough to avoid sedimentation.
2. Protection from predation	1	No protection, because starfish and crabs can easily climb the structures and get to the attached oysters.
3. Effective waterflow	5	Many large holes are incorporated which channel the waterflow.
4. Low price	1	3D printing from sandstone results in high price. Heavy structures make the transportation and deployment costs expensive.
5. Fast deployment	1	Deployment process is slow because each structure needs to be lifted carefully with a crane. Due to large weight and equipment used, additional safety protocols need to be followed which slow the process down.
6. Withstanding bottom currents	5	Structures are heavy and can withstand high waterflows
7. Micro-habitats	5	Shape is highly varied, with many holes and bumps. Structures introduce a wide variety of waterflow speeds and places for other species to hide.
8. Minimal care to fall to the right position	1	Extreme care has to be taken due to safety protocols while operating the crane and lifting these heavy structures.
9. Lightweight	1	Heavy structures (200 – 550 kg) can only be lifted with heavy duty equipment.
10. Integration into the hatchery	1	Large and heavy structure – impossible to integrate into the hatchery.
11. Possibility to locate	4	Easy to locate. Harder to attach location sensors if needed.
12. Minimal need to retrieve	5	Sandstone is a naturally occurring material. Therefore, the structure can be left to degrade on the seafloor.

E) Reef balls (Figure 30 – E). Designed as an effective breakwater system, these reef balls facilitate biodiversity by incorporating cavities all over the structure which are perfect for predatory fish and other biota. However, if used for oyster reef regeneration where oyster larvae numbers are low or non-existent, reef balls share similar drawbacks to 3D printed reefs: expensive to make and deploy, offer no protection from predation, and a very limited amount of oysters that can be deployed with one structure. In addition, they are made of concrete which according to Dutch legislation must be taken out after the legal permit period has ended. More detailed evaluation can be found in Table 9.

Table 9: Solution E evaluation per criteria and explanation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	5	Structures can raise the oysters high enough to avoid sedimentation.
2. Protection from predation	1	No protection, because starfish and crabs can easily climb the structures and get to the attached oysters.
3. Effective waterflow	5	Many large holes are incorporated which channel the waterflow.
4. Low price	1	One standard reef ball of 1 m height is moulded from 1350 kg of concrete. Oysters need to be manually glued to the surface.
5. Fast deployment	1	Deployment process is slow - each structure needs to be lifted carefully with a crane. Due to large weight and equipment used, additional safety protocols need to be followed which slow the process down.
6. Withstanding bottom currents	5	Deigned to act as a breakwater, structures are heavy and can withstand very high water currents.
7. Micro-habitats	5	Cavity inside the reef ball acts as good refuge for many types of fish. Rough outside texture allows organisms to cling and grow on the surface.
8. Minimal care to fall to the right position	1	Extreme care has to be taken due to safety protocols while operating the crane and lifting these heavy structures.
9. Lightweight	1	Heavy structures (1350 kg) can only be lifted with heavy duty equipment.
10. Integration into the hatchery	1	Large and heavy structure – impossible to integrate into the hatchery.
11. Possibility to locate	5	Structures are large and stable - easy to locate.
12. Minimal need to retrieve	1	Structure is made of concrete which is not a naturally occurring material and degrades very slow. According to Dutch legislation it must be taken out after the legal permit period has ended.

Conclusion

The effectiveness of the solution mainly depends on 2 categories (“Oyster survival” and Scalability”) all 5 criteria equally important. Solutions B, D, E partially address the oyster survival but underperform in scalability: manufacturing is expensive, deployment is slow and, therefore, expensive. Solution A performs well in scalability but does not address oyster survivability. Only solution C shows better performance in terms of oyster survival, but multiple scalability challenges were highlighted. Overall, scalability challenges seem to persist in the current solution space and are interesting to explore in this project, while improving oyster survival at the same time.

CHAPTER 3:
DESIGN DIRECTION

3.1 Methodology

3.2 Biomimicry to design

3.3 Shells bound with a medium

3.4 Shells bound with external structure

3.5 Evaluation

Sea anemones (Actiniaria) - inspiration for one of the design directions.

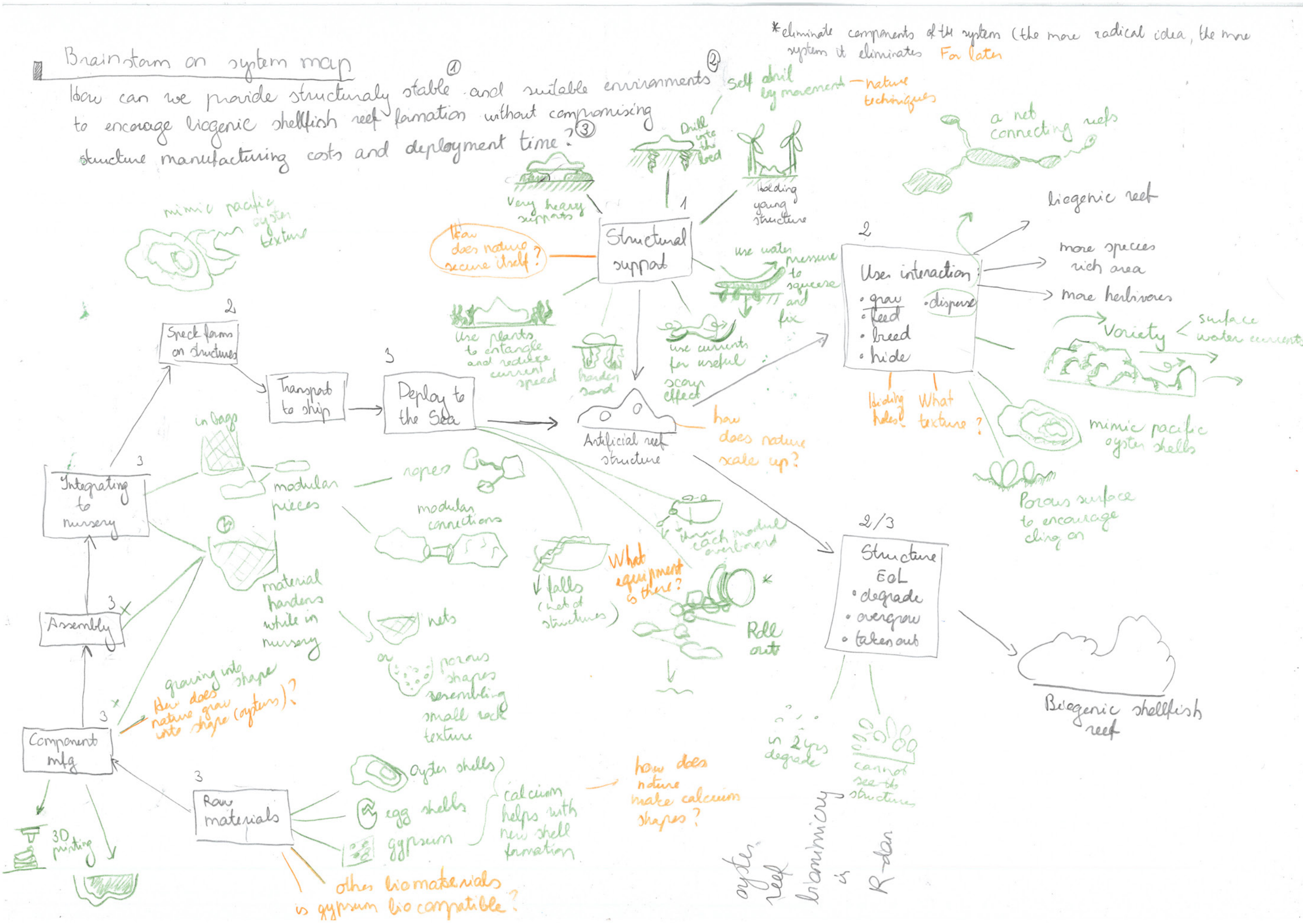
3.1 Methodology

Insights from Chapters 1 and 2 were translated to design by exploring possible design directions. Idea generation was guided by the Whole System Mapping method. The system map of the current approach (Chapter 2, Figure 28) was used as the basis to brainstorm new ideas on how to address oyster protection, scalability, and stability on the seabed (Figure 31). In addition, several possibilities were explored to reduce the steps in the System.

During the brainstorming session, several questions have been highlighted (Figure 31, in orange), and three of them were used as prompts to research nature strategies using Biomimicry: challenge to biology method. Prompts were formulated as: “How does nature stabilize itself?”, “How does nature provide varied environment?”, “How does nature protect itself?”. For the questions, nature strategies were collected from Asknature.org. In addition, desk research was conducted to find whether and how these nature strategies are applied in design for restoration projects.

These insights have been translated into new ideas and low-fidelity prototypes (sketches, clay models) which were evaluated during the weekly meetings with experts from ARK and bi-weekly meetings with design experts. According to the feedback, two promising design directions were highlighted, which were tested using more defined prototypes (3D printed scale models, and models from prospective materials). Both directions were evaluated using design criteria described in Chapter 2 and summarized in the Decision Matrix.

Figure 31: One of the brainstorms done on the system map with highlighted questions acting as possible prompts for further research and inspiration using Biomimicry method.



3.2 Biomimicry to design

Multiple nature strategies have inspired two different design directions (Figure 33). More detailed design direction exploration is described in Appendix A.

Nature strategies for protection were found by looking at the actual oyster reef: by clustering together, oyster shells create numerous gaps, cracks and crevices which provide shelter for young oysters to grow by making it harder for predators to access these small gaps.

For stabilisation on the seafloor, few marine organisms have found interesting ways to adapt. For example, the Sand Dollar can have multiple holes in its body which channel the water through them and reduce waterflow pressure. Anemone, on the other hand, has provided inspiration for its torus-shaped upper part, which can adapt and stay stabilized in currents from different directions. For providing variety, inspiration was taken from the same shellfish reef ecosystem: by clustering many individuals together, numerous varied shapes and irregular surfaces are created, which in turn provide a varied environment for other marine species. Creating a cluster from multiple units seemed to be an effective idea to stabilize the structures in waterflow as well as provide more variety (Figure 32).

Figure 32: Cluster idea from the first iteration: separate units forming a cluster.

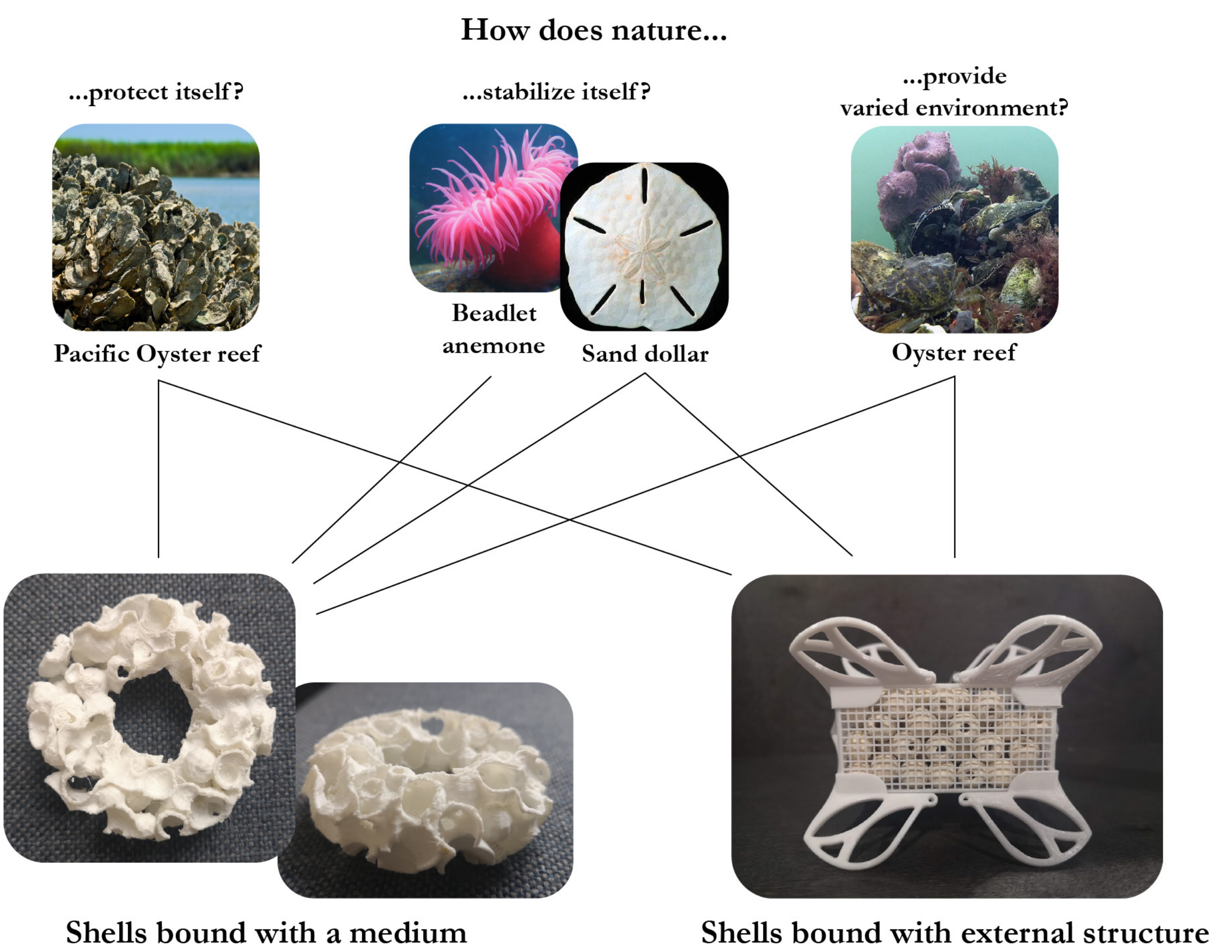


Figure 33: How separate nature strategies impacted two different design directions.

Translating biology to design: two main directions

With the insights from Context Analysis (Chapter 2) and Biomimicry, it was clear that working with empty shells seems to be a promising direction. Firstly, oyster shells and their shape are already highly irregular introducing the needed variety to the structure design. Secondly, using empty oyster shells as a waste source from restaurants reduces the need for virgin materials and returns useful nutrients back into the sea. Therefore, it was chosen to use oyster shells as a medium for the design. There are multiple ways the shells could make these structures, the main design directions were categorized between "Shells bound with a medium" and "Shells bound with external structure".

3.3 Shells bound with a medium

For this direction, the task was to mimic the oyster reef structure and find ways to glue oysters back together into a desired shape. Inspiration from Nature strategies (see Figure 32) has been translated into design in multiple ways. Torus shapes (Figure 34), inspired by Actinia provide good stability on the surface because even if they fall on any edge, they will eventually drop on one of the two major sides. Using them as modules to make a cluster could offer even more surface variety if structures fall slightly on each other (Figure 34). High surface area/volume ratio, crenelations and sharp edges provide an effective surface for oyster spat settlement and protection against predation. Incorporated holes (inspired by the Sand Dollar strategy (Figure 32)) allow some water to go through and act as pressure-drainage places making the structure more stable against the water currents.

Material

For the shell binder, materials with calcium such as gypsum, chalk or limestone have proven to be very useful for oyster formation and growth, because calcium carbonate is one of their main shell-building materials (Yoon et al., 2003). BESE-reef paste comprises 80% ground shells and 20% bio-based binding additives (BESE products, 2021), it was tested out as a possible binder for empty

Figure 34: Design process from an idea to scale prototype and material testing.

Dimmensions:
d= 22 cm
h= 8 cm

Weight before applying paste: 0,695 kg

Weight after applying paste: 1,562 kg

Weight dry sample: 1,370 kg

Oct 27th: Paste mixed with shells → Oct 31st: Sample is still in the process of setting, brittle. → Nov 7th: Sample is dry, structure is strong enough to be taken out of the bowl. → Nov 22nd: Sample shattered into small pieces after moving it.

Figure 35: Sample A weight and test timeline.

oyster shells. The test has shown that while the material composition seems to be beneficial for benthic growth, the binding material is too heavy and too brittle (Figure 35) to fulfil design requirements for handling this type of design during offshore deployment. Weight could be decreased by adding more shells to the structure, but this would further increase the brittleness. By using reef paste in this way, the concept runs into the inevitable limitations of calcium carbonate-based materials being heavy and brittle.

3.4 Shells bound with external structure

The second direction was inspired by the current approaches from ARK, other reef restoration organizations and oyster farms, where young spat on shell are put into oyster crates or steel mesh boxes (Figure 36).

To solve challenges related to the deployment of ARK's model (Chapter 2, Table 7), new design possibilities were explored:

1. **Connected units:** by connecting the units either in a row or in a cluster and deploying them all at once, deployment time is drastically reduced, less manual labour is needed, and the system can be further automatized. The inspiration comes from the technique used to catch lobsters in the North Sea (Figure 37).
2. **Limiting rotation axes:** When units are connected in a row (Figure 38) and pulled from the deck of a moving ship to the seafloor, they will rotate mostly around the longitudinal axis when falling onto the seafloor. Lateral and vertical rotations are minimized due to the tension between the pulled units. Therefore, only the longitudinal axis needs to be considered when designing support structures to raise the unit from the seafloor.

Figure 36: One of the prototypes developed by ARK using metal wire mesh to pack empty oyster shells. Photo credits: Ernst Schrijver Ark Rewilding Nederland

Figure 37: deploying cages to catch lobsters. All cages are connected in a rope and deployed in a row. Photo credits: Wiron de Beleyr

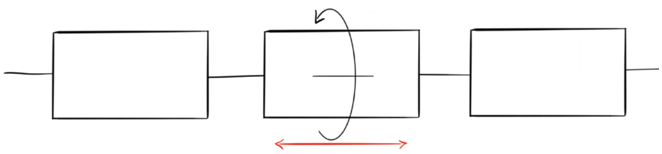


Figure 38: When units are connected in a row and pulled towards the seafloor, they will rotate mostly on the longitudinal axis. Other rotations are minimized.

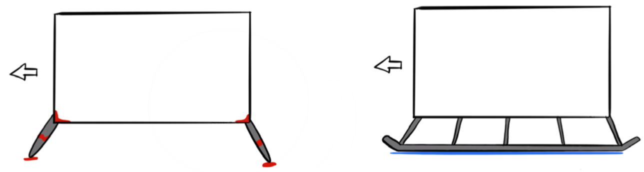


Figure 39: Different support legs can impede or facilitate sliding on the surface.

3. Sliding: If the units would be deployed in a row, pointed legs from the current design would increase the friction on the deck surface and could break off when being pulled. Instead, a support structure could facilitate sliding on deck, similar to a sleigh (Figure 39).

Designed structure (Figure 40) functions in any longitudinal rotation position – no matter how much cradles will rotate around the longitudinal axis before falling onto the seabed, the supports will always raise them 200mm above the seafloor. Assembly is made easier due to the interlocking part between the support frames. The shape of the supports facilitates sliding: a bent outline distributes the compression stress more uniformly and does not block the sliding movement if any surface irregularities or bumps are met along the way. The inner wing surface was cut out to mimic the sand dollar strategy to better withstand the waterflow and minimize the weight.

Material

The materials used for the oyster crates vary: oyster farmers often use baskets made of polypropylene for off-bottom farming, and oyster restoration projects sometimes use steel mesh (Figure 36) because carbon steel comprises non-toxic elements of carbon and iron. However, these meshes are usually galvanized (coated with a layer of zinc) to protect the mesh from corrosion and increased concentrations of Zinc or Zinc Oxides can negatively affect various marine organisms (Sarker et al., 2021; Yung et al., 2014). Therefore, if the steel mesh would be used in the new design, it should be a bare carbon steel mesh without any corrosion protection layers.

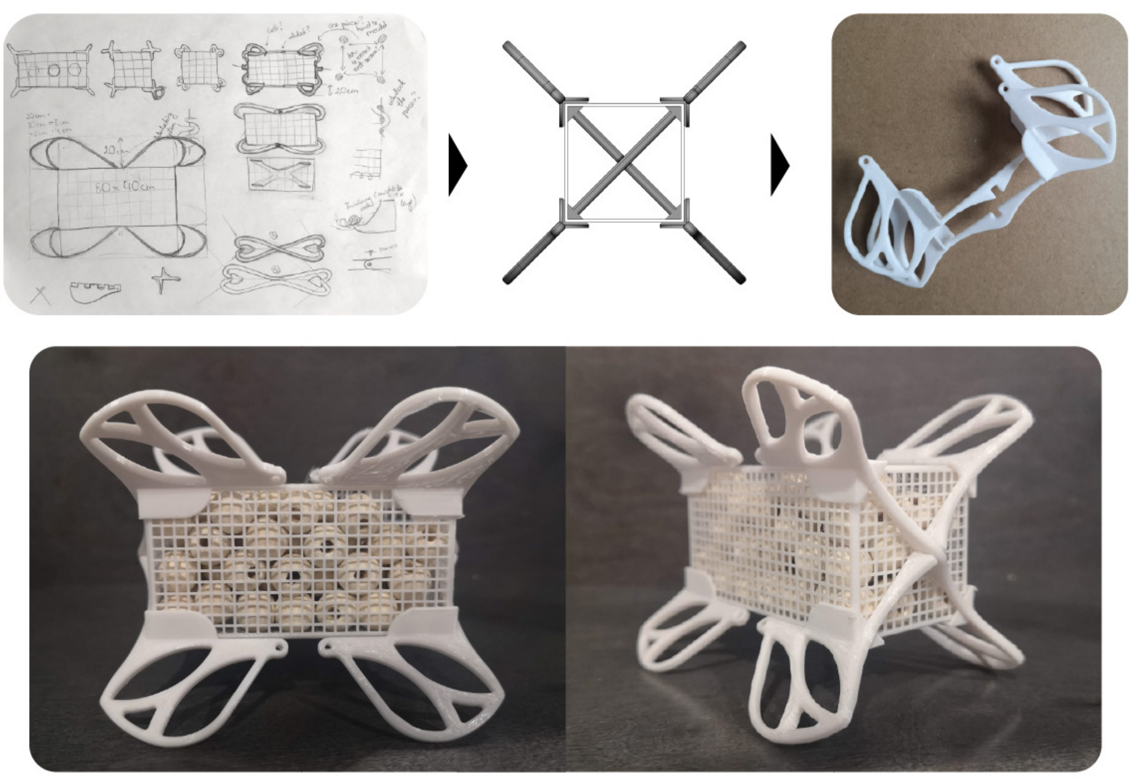


Figure 40: Design process from an idea to a 1:10 scale prototype.

3.5 Evaluation

Two design directions have been explored on an abstract level: Direction 1 - “Shells bound with a medium” and Direction 2 - “Shells bound with external structure”. Testing the concepts with scale models has enabled to gather rich insights which were used for design direction comparison against predefined design criteria (Chapter 2, Table 3). Design evaluations are discussed below and illustrated with a Decision matrix (Figure 41) - the final part of the Whole Systems Mapping method.

- **Oyster survival:** If the shells are bound with external mesh material (Direction 2), the structure will be more lightweight than the shells with a calcific binder between them. Therefore, the structures might be raised from the seafloor more efficiently to avoid sedimentation. Direction 1 might get sedimented more quickly because it sits directly on the seafloor. Both directions employ the same nature strategy of incorporating numerous gaps, cracks, and crevices to protect oysters from predation, direction 2 protection is improved further with the external mesh. Both directions would let enough water through the oysters.
- **Scalability:** Current state of art for direction 1 would underperform in scalability: structures are brittle and heavy, and have to be handled with great care, thus, slowing down the deployment; current binding material is produced only with one supplier, which can have price or manufacturing reliability challenges. The current state of direction 2 has challenges with scalability as well, but both the deployment process and price can be improved further with more design iterations.
- **Broader ecological success:** Direction 1 performs better due to the material composition (natural, biodegradable, calcific) which can facilitate benthic growth, and structures would be stable on the seafloor. Direction 2 in this case might have more challenges withstanding bottom currents because it is more lightweight and raised from the seafloor, also material composition may be less favourable in comparison to direction 1.
- **Deployment and handling:** Direction 1 underperforms in most design criteria because of its weight and brittleness: it would be challenging to integrate them into the hatchery pools, transport them and handle them in an offshore environment without breaking these structures. Once deployed, structures sit on the seafloor and start to degrade, so there is no need to retrieve them, but it will also be

Objective	Weight	Shells bound with a medium	Shells bound with external structure
Protection from sedimentation	5	2	5
Protection from predation	5	3	4
Effective water flow	5	5	4
Low price	5	1	1
Fast deployment	5	1	2
Withstanding bottom currents	4	5	3
Micro-habitats	2	5	3
Minimal care to fall in right position	4	5	5
Lightweight (pre-assembly)	2	1	3
Integration into the hatchery	3	2	3
Possibility to locate	2	2	3
Minimal need to retrieve	4	5	4
	Total Score	142	155

Figure 41: Evaluations reflected by scores in the decision matrix show that the design direction “Shells with external structure” may have more potential in this use case.

more challenging to locate these structures once they degrade into pieces. Direction 2 performs better: structures are more lightweight, and it is easier to integrate them into the hatchery. They will also degrade more slowly and can be located easier, but further ideation is needed to ensure that materials will be suitable to be left to degrade on the seafloor.

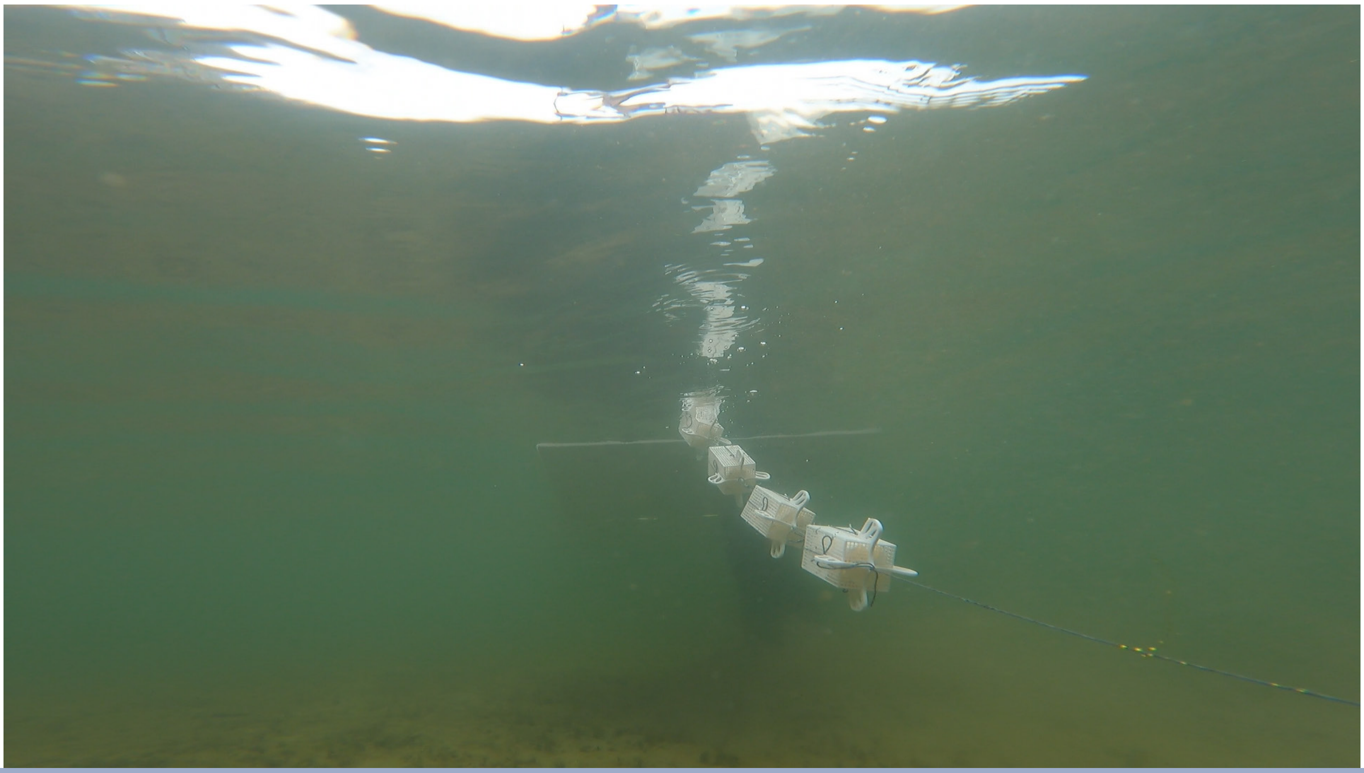
Due to the superior qualities in scalability, structural integrity and oyster protection, direction 2 was chosen to be further iterated. Further iterations in this direction should retain the points of attention:

- **Scalability:** Further improvements on the support structures should focus on minimizing the assembly times and use of material to reduce production and deployment costs.
- **Non-toxic:** The design should ensure that the structures are non-toxic to marine life and can be left on the seafloor permanently without causing damage.
- **Oyster protection:** Choosing suitable mesh material that would keep the shells together and would biodegrade after 1 to 2 years.

CHAPTER 4:
CONCEPT EXPLORATION

4.1 Whole System Mapping
4.2 Concept exploration
4.3 Testing
4.4 Advantages & disadvantages
4.5 Final evaluation

Testing one of the concepts in small scale deployment test.



With chosen direction and insights, further iteration explored several conceptual designs. The ideation began with a new system map, followed by different concept explorations, and was finished with an evaluation according to the design requirements. The evaluation was summarized in the decision matrix and the iteration was finalized by choosing one concept to be developed further in the final design phase. In this chapter, several concepts are discussed which were marked in Figure 42, other concepts or interim results are described in Appendix B.

4.1 Whole System Mapping

The current list of criteria (Chapter 2, Table 3) is very extensive, this could lead to a design fixation or very incremental improvements in the design. Therefore, for this iteration, it was chosen to take four important design criteria and add others during the Whole System Mapping evaluation phase at the end of this iteration. During the current solution evaluation (Chapter 2) it was noticed that scalability while ensuring effective oyster survival is the biggest challenge.
4 design criteria were chosen from the list to reflect this priority and explore the idea space which would facilitate better scalability and oyster survival.

Priority design criteria for this iteration:

- **Structures should be low in price for production, assembly, and deployment.**
- **It should be possible to deploy high volumes of oysters in a short amount of time.**
- **Structures should protect oysters from sand mega-ripples of at least 20 cm in height.**
- **Structures should be designed to protect juvenile oysters from predation (crabs and starfish).**

With these criteria in mind, the main question for the whole system mapping is formulated as:
After having critical design requirements and design questions defined, brainstorming on the system map took place (Figure 43). The base of the system map was kept the same as in (Chapter 2, Figure 28), different colours were used to mark which system part the ideas belong to.

> "How can we make the structures scalable in terms of price and time for deployment without compromising the structure's ability to protect young oysters from sedimentation and predation?"

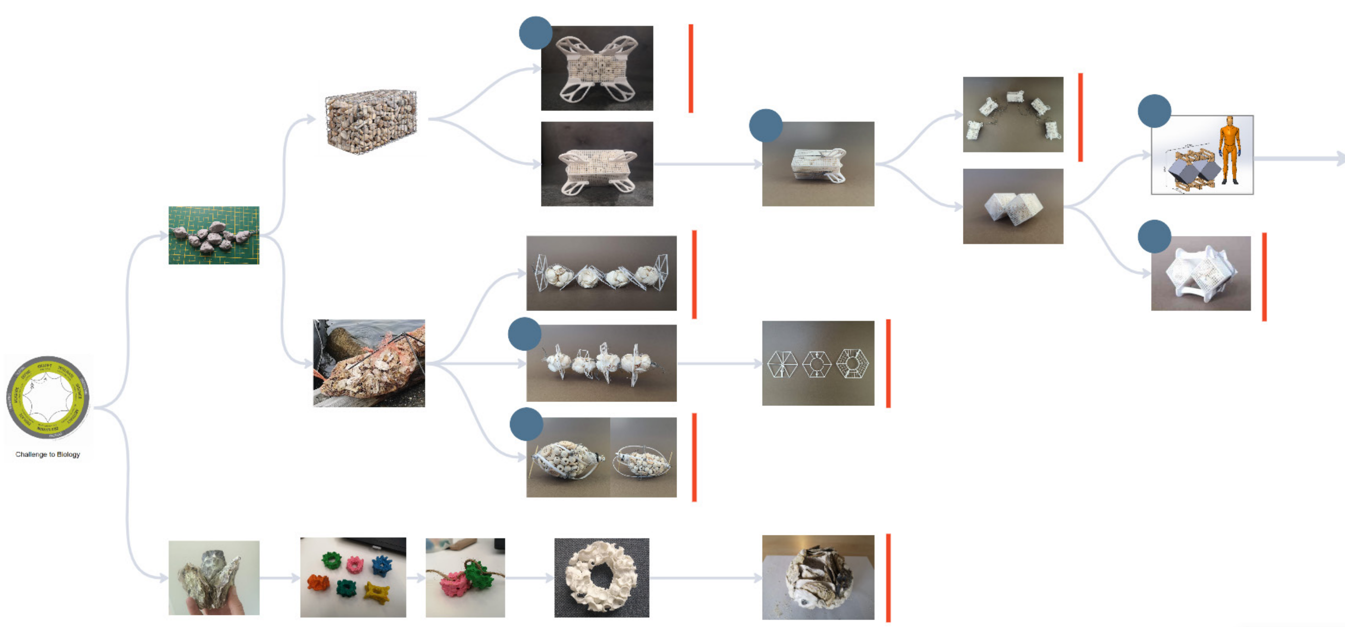
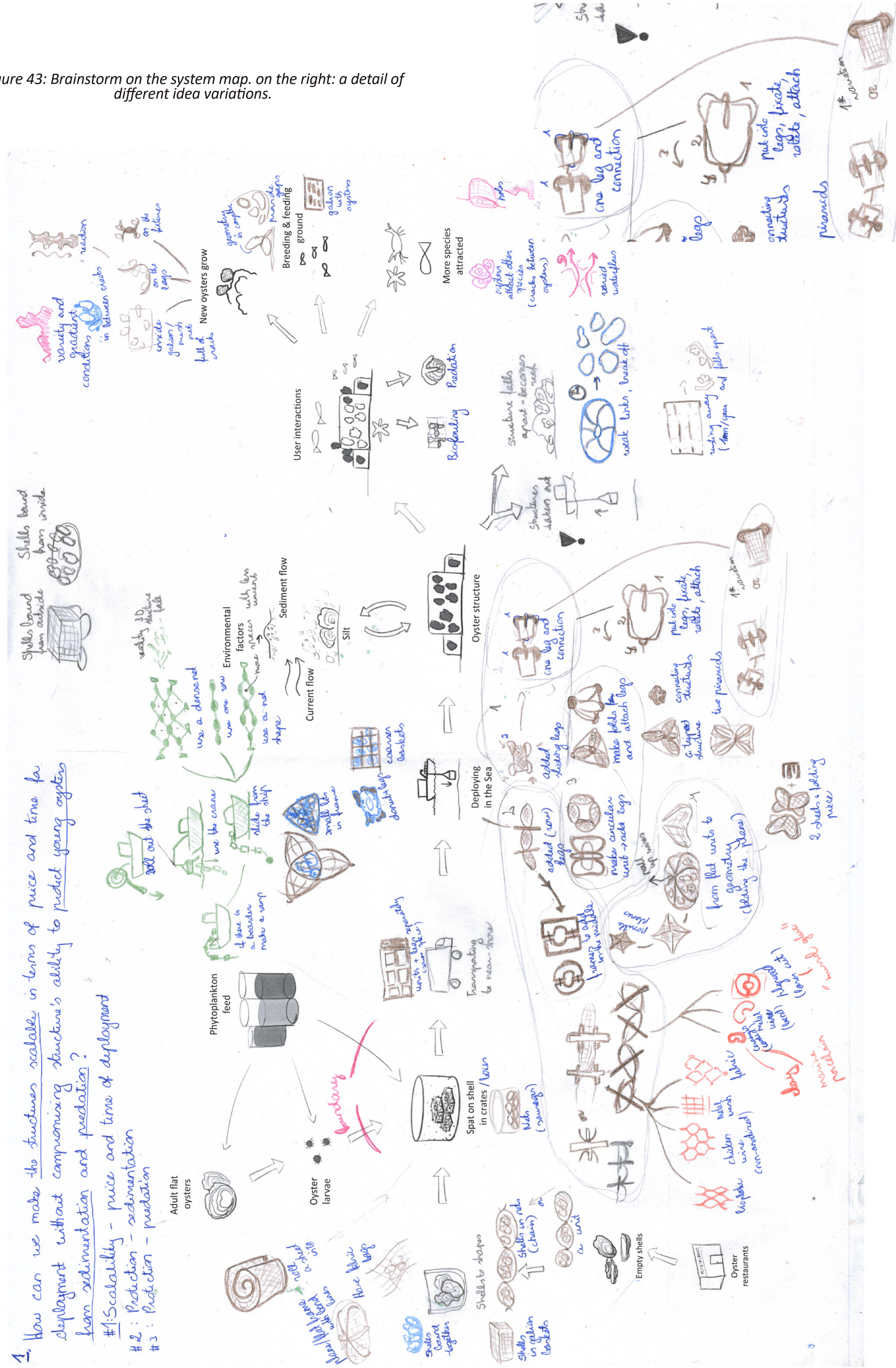


Figure 42: Design exploration and chosen concept direction. Concepts which will be discussed in this chapter are marked with a blue dot.

Figure 43: Brainstorm on the system map. on the right: a detail of different idea variations.



Most brainstormed ideas were related to the deployment part because most scalability challenges arise there, nevertheless, brainstorming also covered other system parts, such as: finding different ways of how structures could be put into water tanks in the hatchery where spat settlement takes place or finding different ways how units could be deployed – in a row, in pairs, with a crane or a roll-out mechanism or by sliding from the deck. Ways to eliminate steps in the system: structures which would be put into the hatchery where larvae settle straight on them. In addition, the mortality of spat on shell is reduced by avoiding transferring them into another structure. Some ideas had a chain effect: For example, the gabion with support structures would be used to raise the oysters from the ground, can the structure be simplified to reduce manufacturing steps? Can the material use be reduced to half?

During the iterative brainstorming, several ideas have emerged:

- The gabion model, similar to the first iteration but with support structures rotated to secure the gabion walls instead of the corners, which could save material and manufacturing costs and reduce steps for assembly. Units could be connected in a row, one by one, or in a net setup (one unit connected to two to one) and an anchor could be used to pull the row into the water.
- Oyster nets, which could be used to form a chain of pouches with support frames mounted between every element or around each element.
- Oyster nets with unfolding support structures which could be folded when the units are transported to the sea and would unfold just before being deployed to the sea. This saves valuable space during transportation and deployment can be automated more efficiently.

Due to a current high abstraction level, it was hard to estimate which concept would satisfy the design criteria best, therefore, these ideas were further elaborated by prototyping (3D printed scale models, high-fidelity real scale models) to gather more insights. These ideas were later evaluated on the full list of design criteria (Chapter 2, Table 3) and summarized in a Decision matrix, which is presented at the end of this chapter (Figure 78).

4.2 Concept exploration

4.2.1 Concepts with oyster nets

Many restoration projects use oyster nets to form living shoreline protection or to introduce oysters to the deeper waters. Usually, these oyster shell bags are made from aquaculture-grade polyethylene and add to an already severe plastic pollution problem (Walters et al., 2022; Nitsch et al., 2021). Approaches which use these polyethylene nets have become increasingly criticised, and biodegradable alternatives are being developed. One of them is the same type of bag (Figure 44) made from biopolymer which is expected to degrade in 3-10 years depending on environmental conditions (BESE products, 2022).

Bags are an efficient way to concentrate oysters together and can be formed into a continuous chain by simply introducing knots in between a certain number of shells (Figure 45). Formation of these chains could be automated, and after being filled with empty oyster shells they could be put straight into the hatchery's pools where spat would fall. When deployed to the North Sea, these bags still need to be raised from the seafloor to limit oyster mortality.

For support design, the main question was how to save space in the hatchery and during transportation phases but provide large enough supports to lift the bags from the seafloor when they are deployed. To facilitate this, designed frames should be attached to the chain or unfold right before the chain is deployed to the sea.

Figure 44: BESE oyster bag made from a biodegradable biopolymer. Image credit: BESE products, 2022).

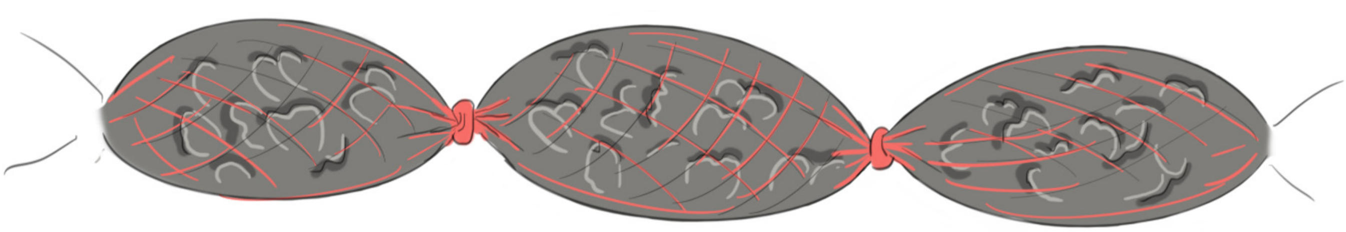


Figure 45: possibility to make several units filled with oyster shells out of one continuous biodegradable net.

Oyster nets with rigid frames

After multiple frame design iterations and tests (for intermediate results, see Appendix B) a final small-scale prototype was developed to secure onto the oyster bags and raise them: with a toothed inner contour the frame can grab and secure onto the oyster bags tight and probability of frame sliding off is reduced; inside the frame, patterned infill adds more strength while retaining a lightweight construction. When each bag is filled with oysters, it becomes less flexible and can offer a more stable basis for the frame. In addition, when on the seafloor, the raised bags would remain straight without falling on one of the sides because each bag is pulled and tensed by other bags.

Oyster nets with unfolding frames

Instead of the necessity to attach the frame manually right before deployment, the frame could unfold automatically when it is needed. By mimicking the basic clicking pen mechanism (Figure 48) it is possible to twist the frame around the oyster bag and lock it (Figure 47). A frame will unfold automatically when pull force is applied to the ends of the bag (Figure 47). The bags with a winded-up frame would be stored in a roll to save space. When a chain of these bags is unrolled into the water, every few seconds the roll would stop and certain bags' edges would be pulled due to inertia. The pull then would release the lock mechanism, and the frame would unfold right before entering the water. In this way, no active human intervention would be needed during the deployment.

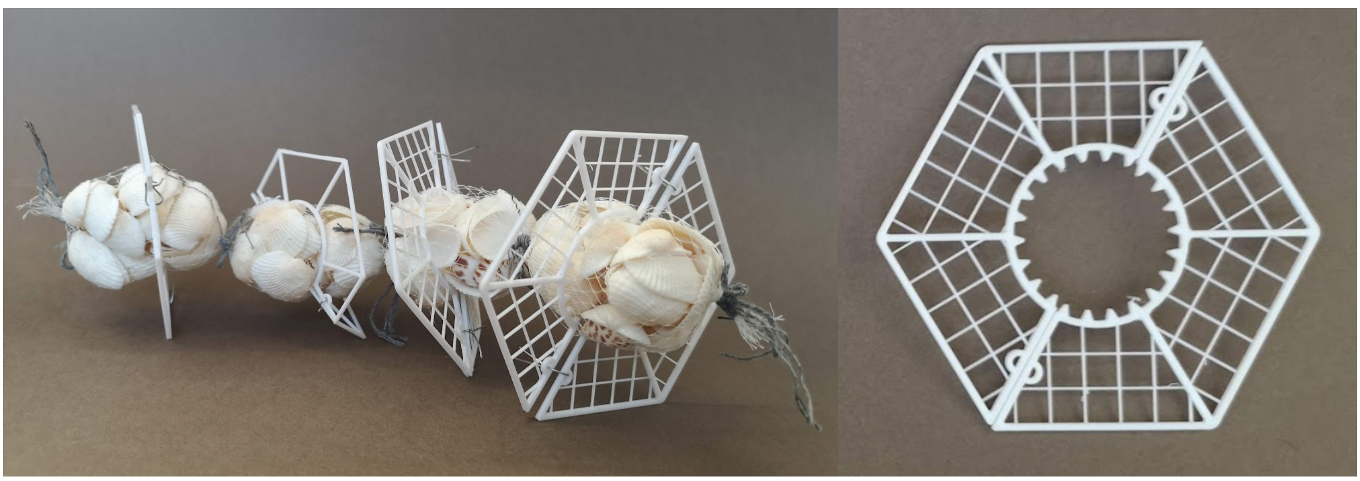


Figure 46: Left - oyster bags with frames from two iterations, right – last frame design iteration.

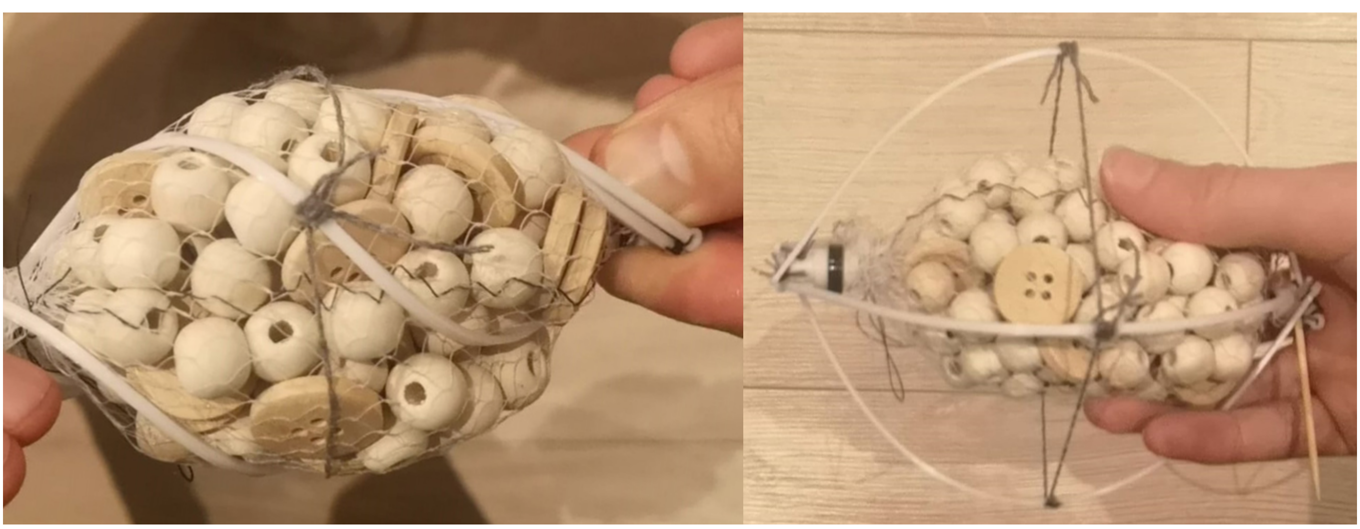


Figure 47: Prototype for the unfolding frame. Left - the frame is winded up around the oyster bag, right - once the mechanism is pulled, it releases the frame and it unfolds like a spring.

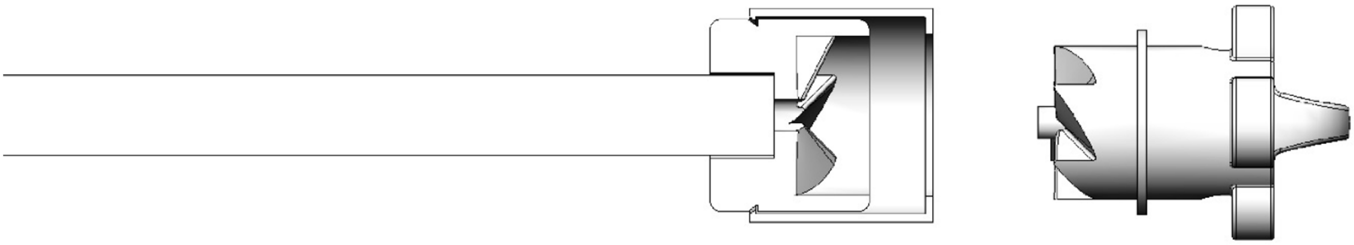


Figure 48: 3D model of the wind-up lock which mimics a common click pen mechanism. It is possible to twist and wind up the frame in one direction, but the frame cannot unfold because the ladder is blocking a rotation to the opposite side. The lock can only be released when the head (on the right) is pulled away from the groove (on the left).

4.2.2 Concepts with gabion baskets

As an external structure holding the oyster together, gabions made of steel mesh are integrated in several different design directions. Gabion baskets are already used in the oyster reef and shoreline restoration projects due to their structural strength (Walters et al., 2022; EcoShape, 2020). If exposed to the environment, steel mesh is prone to erosion, which, in this project, is a desirable outcome because it will give grown oysters more space to grow. According to the ergonomic and technical requirements, gabion measurements can be adjusted. For this support design iteration gabion size of 400x400x800 mm was chosen due to optimal size while handling and minimizing the use of steel per oyster batch.

Supports offer a range of other functions: they provide more structural integrity for the gabion basket during the deployment, position the basket in a preferred position on the seafloor, and stabilize the structure against the water currents. For the support design, the main goals included minimizing the material use and reducing the costs of manufacturing while maintaining the aforementioned functions.

Figure 49: gabion baskets used for oyster reef restoration. Image credit: EnZar (n.d.)

Gabion basket with supports

The support design for this iteration secures onto the walls instead of the corners (Chapter 3, Figure 40) and rotates the gabion 90 degrees in a diamond position. Once deployed on the seafloor, the gabion would sit on one of its edges (Figure 50), so supports need to be added only on one side to guide this position. To minimize material use for the supports, the topographic optimization method was used with a 2D TopOpt app (DTU & Aage, 2020). In addition, this one-sided design reduces steps in assembly and can save deployment time on a ship deck. Structures can be connected in a row, which is attached to the anchor and deployed all in one go (Figure 51, Figure 52).

Compared to the concept with corner supports (Figure 53) material use is drastically reduced: this design uses 68% less material with fewer manufacturing steps and easier, faster assembly. However, one of the gabion's edges will be touching the seafloor, so some oysters would get sedimented and suffocate. For theoretical sedimentation impact calculation, it was considered that oysters which are at least 20cm above the seafloor will survive, and the ones which are less than 20cm above the seafloor will be lost, because of the sand mega-ripples described in the design criteria. According to this calculation, when gabion is in a diamond position with one of its edges touching the seafloor, 20% of oysters would be sedimented and lost.

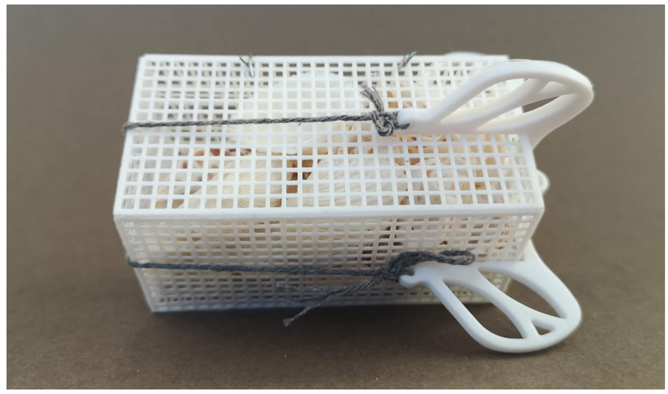


Figure 50: Design with supports on one side.

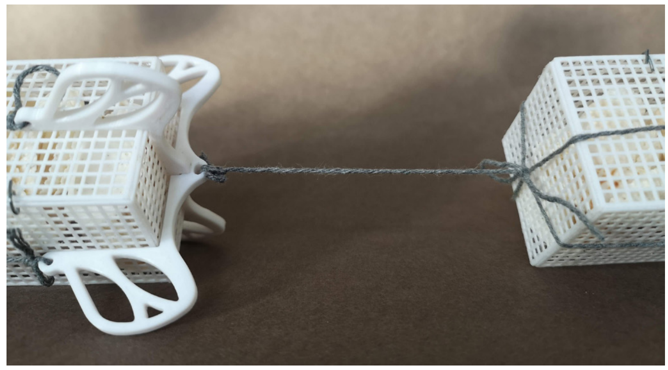


Figure 51: Connection between two units.

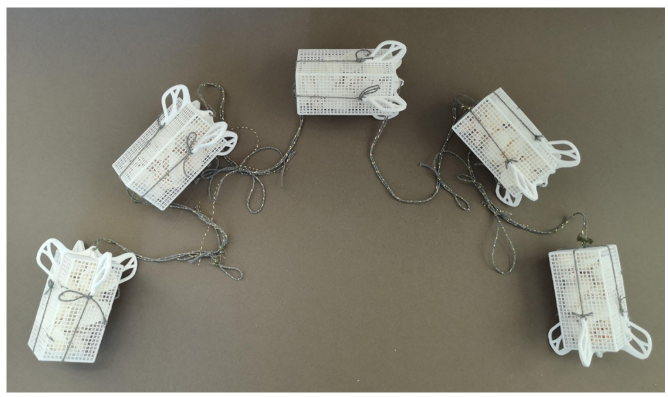


Figure 52: Units connected in a row, while testing deployment arrangements.

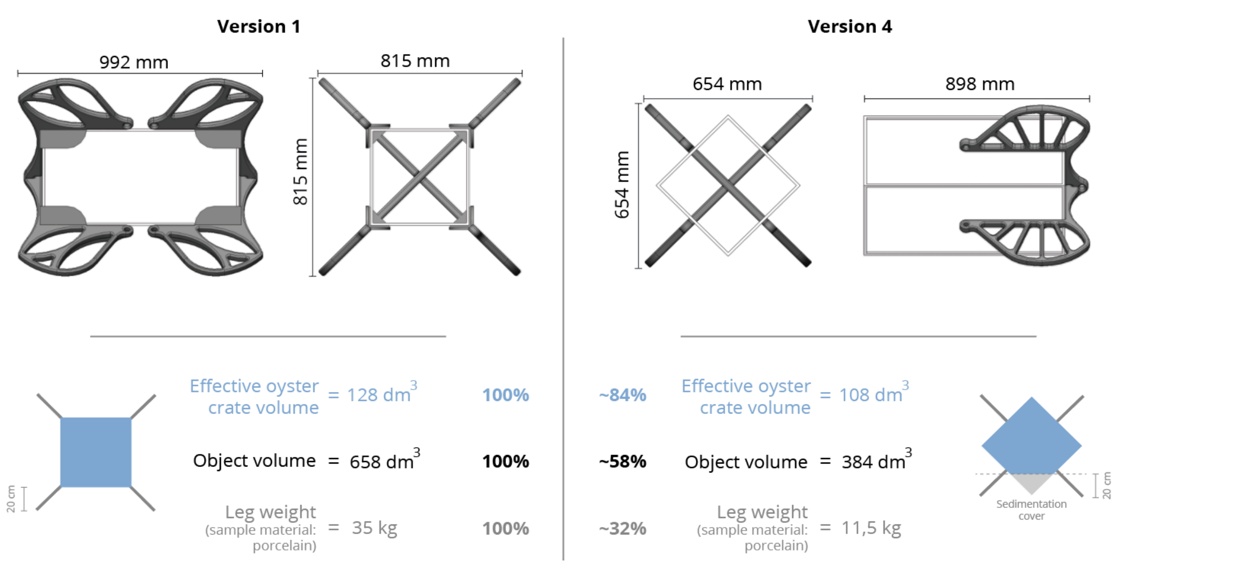


Figure 53: Comparison of support structure designs: on the left - design from the first iteration, on the right - structure from the fourth iteration.

Two gabions between CNC frames

There is also a possibility to connect the two gabions together on the edge to make a double diamond shape (Figure 54). Because the middle edge connection already holds gabions in desired diamond position, the support structures can be designed to raise the gabions more efficiently and save more oysters from getting sedimented. One of the possibilities is to use a support frame which would raise the gabions from two sides and ensure that the whole structure falls or tilts on those desired sides. Due to their geometry, the frames can be cut from solid wood planks using CNC machinery. The top and bottom frames are identical, making them easier to manufacture and assemble. By implementing grooves and bumps on the support parts, the gabions are secured from sliding off the structure in all directions (Figure 54, Figure 55).

Assembly is quick and simple: firstly, the bottom frame is assembled from 4 parts. Then two gabions are placed into the designated grooves and connected together. The top frame is assembled and put on top. All structure is secured from two sides with jute lashings and clam buckles. The assembly is then connected to another unit and the row is formed.

The unit may fall in two positions: upright – in that case 97,7% of oysters are above the 20cm sedimentation line, and sideways – 79,7% of oysters are above the sedimentation line (Figure 56). Further testing should be done to determine what is the possibility the structure lands sideways.

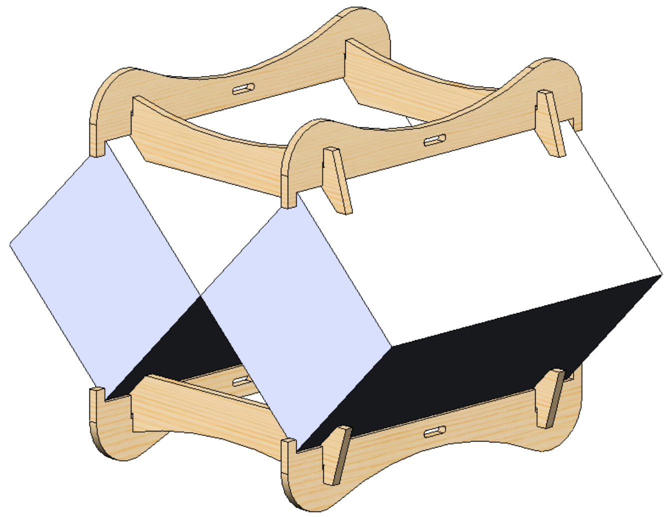


Figure 54: Gabions are secured with grooves and bumps to stay in place.

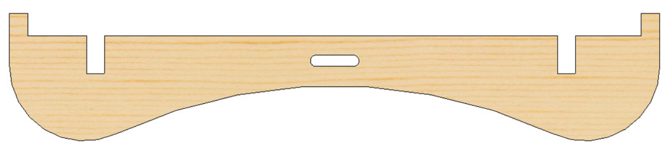


Figure 55: Side view of the support leg.

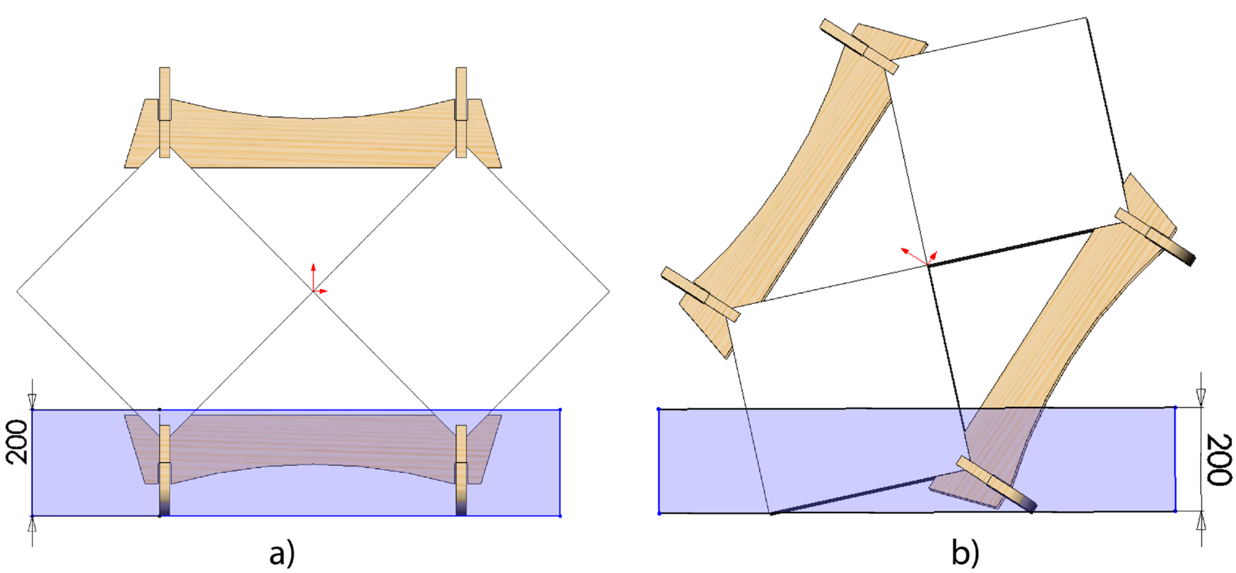


Figure 56: Positions of how a unit might fall: a - intended upright (97.7% oysters above the sedimentation line), b - sideways (79.9% of oysters above the sedimentation line).

Two Gabions between pallets

For a more standardized solution, half-euro pallets or display pallets can be used as a base to raise the gabions from the seafloor and provide structural integrity during transportation (Figure 57). Different types of euro pallets are used in many logistics operations. They are designed to endure the rough handling process, manufactured from solid wood planks, the dimensions are on the agreed standard: 1200x800 cm - a euro pallet, 600x800 cm – half euro pallet with maximum load capacity for half-euro pallet being 500kg. Euro pallets have also clearly defined treatment standard ISPM 15, with treatment methods marked on the pallet (Figure 58) (HT – heat treated, DH - dielectric heating, MB – methyl bromide fumigation). According to the ISPM 15, from 2015, the use of methyl bromide is phased out for common application (Sela et al., 2017) and in the EU, treatment with methyl bromide is banned from 2010 due to negative impacts on the environment (FEFPEB, 2012). Therefore, heat-treated pallets are mostly used and would be suitable for the marine environment because no additional chemicals are added to the wood.

Half-euro pallet size standard dimensions are 800x600 mm, therefore gabion dimensions need to be adapted by making them wider but shorter to fit on the pallet: 450x450x550 mm. The whole assembly (Figure 57) is 1300x900x600 mm and has a simple construction: two gabions being sandwiched by two support structures, with everything tightened together with a lashing.

Figure 57: One of the pallet designs, one unit assembly.

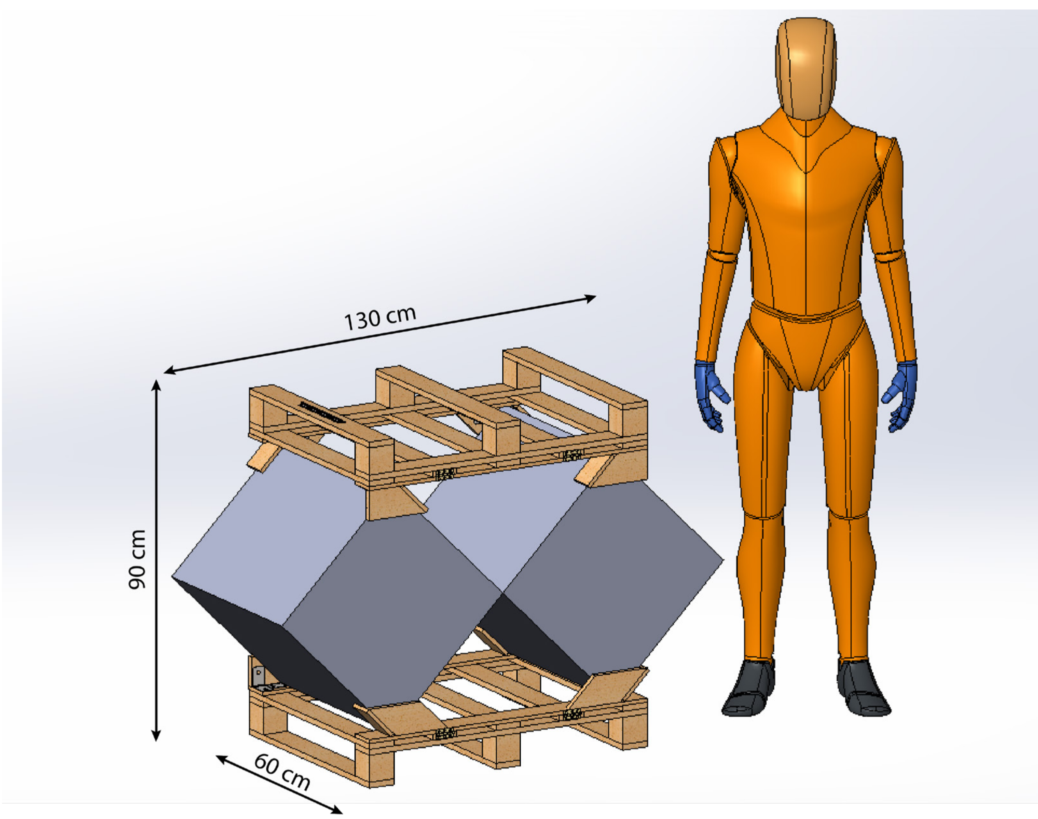


Figure 58: Markings indicating that the EPAL pallet is heat treated. (Image credit: Vigidas Pack, 2023).

4.3 Testing

During the prototyping phase, it was noted that some of the outcomes were unknown for a few interim or final concepts. The main unknowns were:

- Oyster nets with support frames (interim solution) – behaviour underwater, will the interim frame solution provide attach efficiently enough to not fall off?
- Gabion basket with supports from one side (interim solution) – behaviour underwater, the probability of them falling into different positions, and possible ways of deployment.
- Gabions with pallets (final solution) – 2 design ideas were tested out with full-scale prototypes to evaluate their structural integrity.

For interim solutions, test results have been translated to design improvements and final concepts presented in Chapter 4.2. For the final solution, the test results have impacted the choice of one final design solution.

4.3.1 Testing oyster nets with support frames

Multiple unknowns have emerged while developing a frame design to support the oyster nets. The interim solution was made and had a clear and smooth inner ring (Figure 59), it was unclear whether tensing these frames onto the oyster bag will be enough to ensure they will not fall off during deployment. Testing out the prototype in an underwater environment would provide much more valuable insights.

Testing & insights

A prototype (scale 1/10) was tested out in the lake to see how it is affected by multiple deployments into the water (Figure 60). The support structure effectively raised the oyster bags from the sand floor (Figure 61) but after a few additional drops, some frames started to fall off and oyster bags ended up on the sand floor (Figure 62).

Outcome

The test has shown that tightening the frame onto the oyster bag with the inner ring is smooth, does not provide enough grasp and the concept runs into the risk that the frames will fall off once the units hit the water. The final iteration was done to improve the frame design which included a toothed inner circle which grasps onto the oyster bag much more effectively (Figure 46, right).

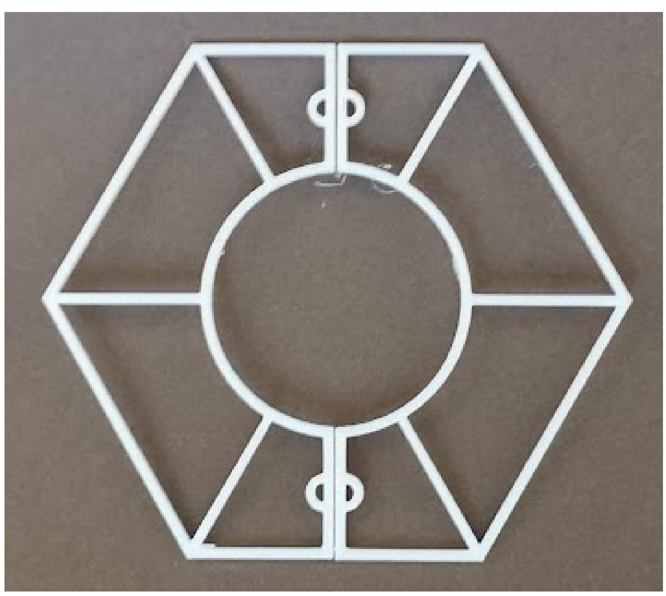


Figure 59: Interim solution for the "Oyster nets with support frames" concept.

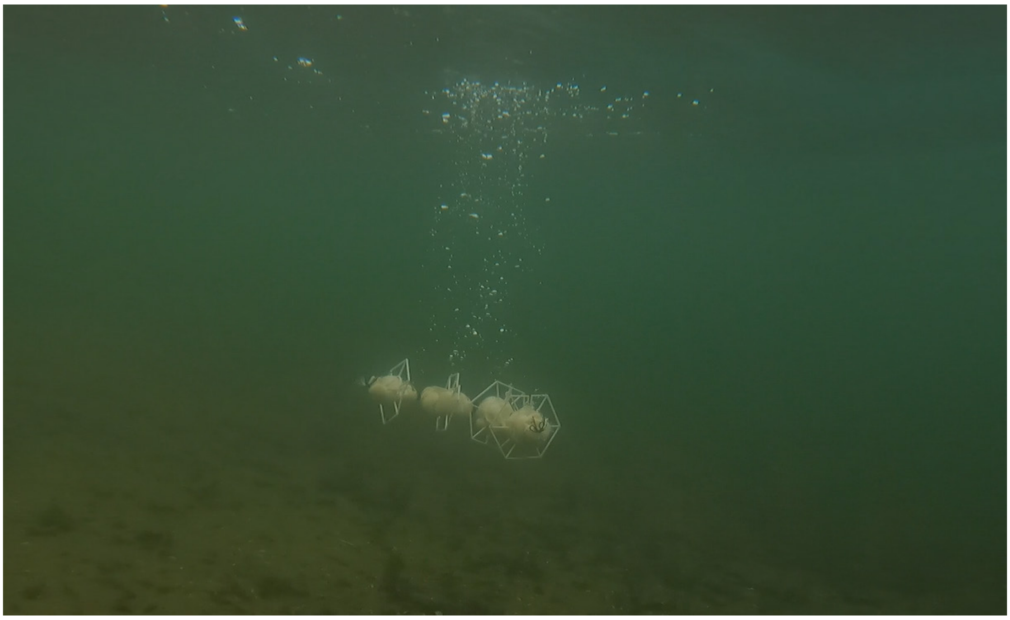


Figure 60: Assembly is thrown into the lake water.

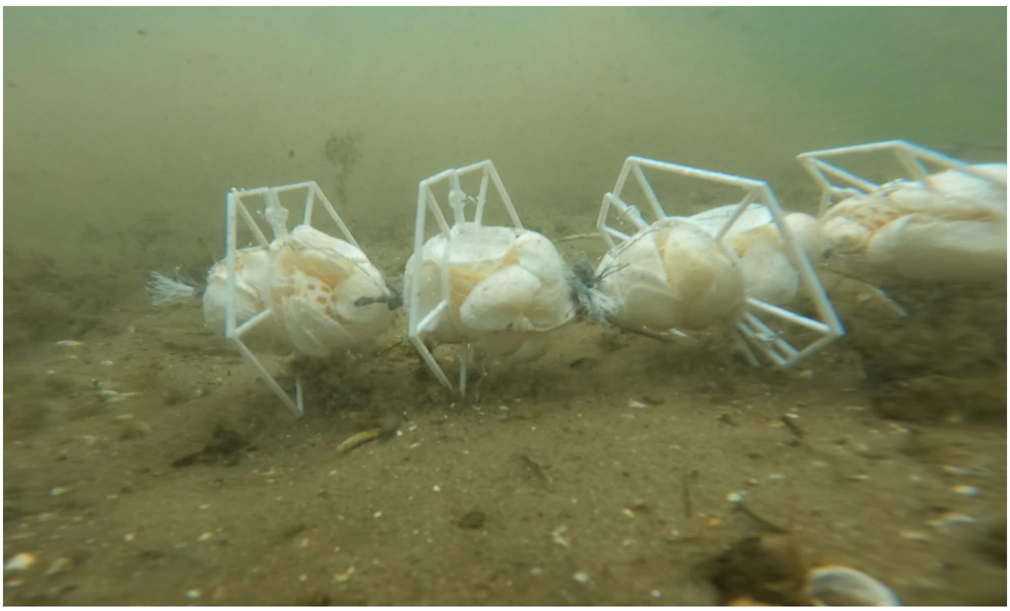


Figure 61: The frame stands upright and raises the bags from the floor.

Figure 62: Supports sliding off the oyster bags after multiple throws into the water.

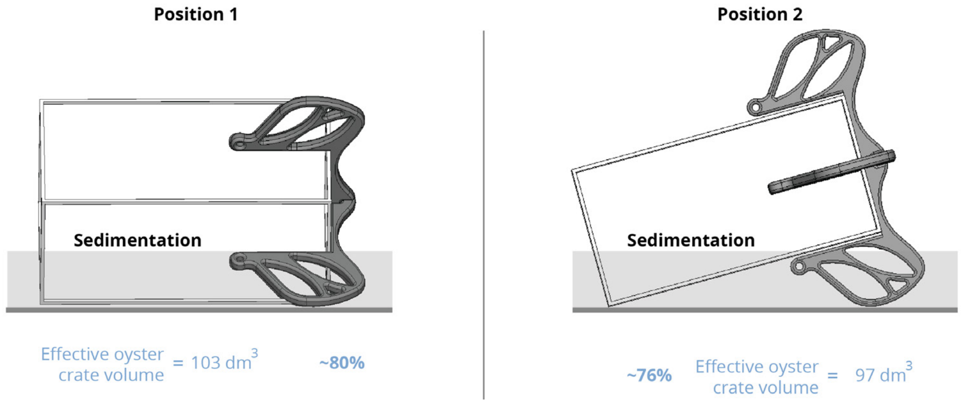


Figure 63: Comparison of the different positions of how the structure can fall on the seabed.

4.4.2 Gabion row with supports

While developing single gabion supports only on one side, few unknowns have been noted. Firstly, with one-sided support, the structure might fall in a less desirable position with a front gabion edge and one support structure touching the seafloor (Figure 63). It was calculated that this position would increase the oyster loss: a 24% loss compared to the desired position (80% of survival). Secondly, several different unit arrangements were possible on the deck (Figure 64) with varied rope lengths between each unit. Testing included observations about how often the units would fall in each position.

Testing & insights

A test was planned with 1/10 scale models in the lake with a foam sheet as a boat. Deployment of the gabion model in several different arrangements and different depths (40 cm and 75 cm) was done to see how it impacts units' fall position and determine possible deployment challenges (Figure 65).

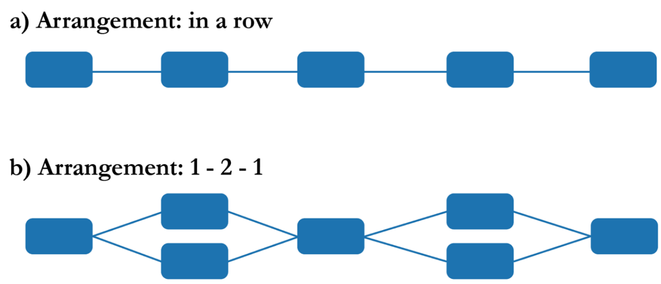


Figure 64: Two types of arrangements have been tested.

Figure 65: Scale model deployment in 75cm depth. Models arranged in a row.

Sometimes structures fall into the “shark” position which is undesirable (Only one support leg touches the sand floor), see Figure 66. Usually, units fall into the right position (Figure 67), especially when the ropes are longer between the modules. This gives more time for each module to fall down, and its’ position is less affected by the modules next to it. The negative side of a larger distance is that with longer ropes, the chance of entanglement is drastically increased. During one of the deployment tests, the rope tangled with one of the modules (Figure 68). Water currents were mimicked with a kayak paddle, and it was noticed that the structures rotate and stabilize in the upright position (Figure 67).

While testing out the different module arrangements, one of the ARK experts mentioned that rope loops on the ship deck need to be avoided, due to safety concerns. This also applies to the arrangement where modules are connected in a row in 1 – 2 – 1 (Figure 69). Interestingly, when units fall in this arrangement, they create more gaps between each other where the waterflow will be slower (Figure 70), which could be beneficial for other benthic species.

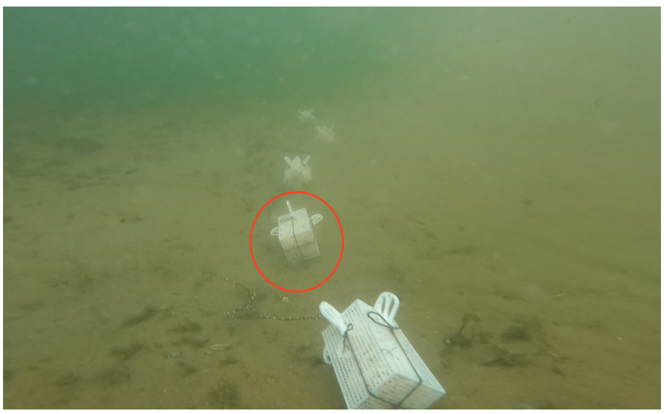


Figure 66: Some units fall into the “shark” position (circled in red), which is undesirable.

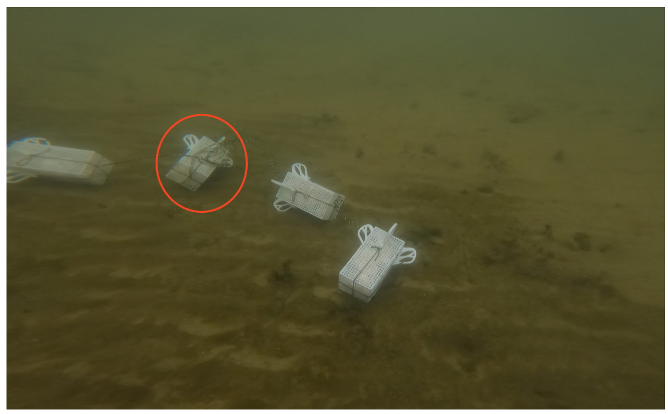


Figure 68: One of the units got entangled in a rope.

Figure 67: One of the units is in an upright position with a rope connecting to another unit.

Figure 69: Units are arranged in a way that one unit connects to two, then one again.

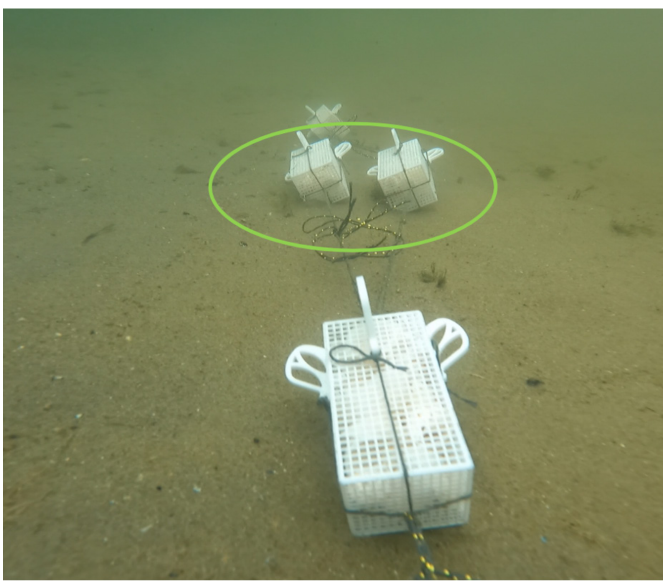


Figure 70: Gap where the water current might be much slower, allowing other organisms to grow.

Outcome

It was noted that longer distances can positively impact the falling position but increase the possibility of entanglement. This has led to increasing the size of supports slightly in the final version of this concept, so they would guide the gabions to fall in the right position more effectively and raise them more from the seabed.

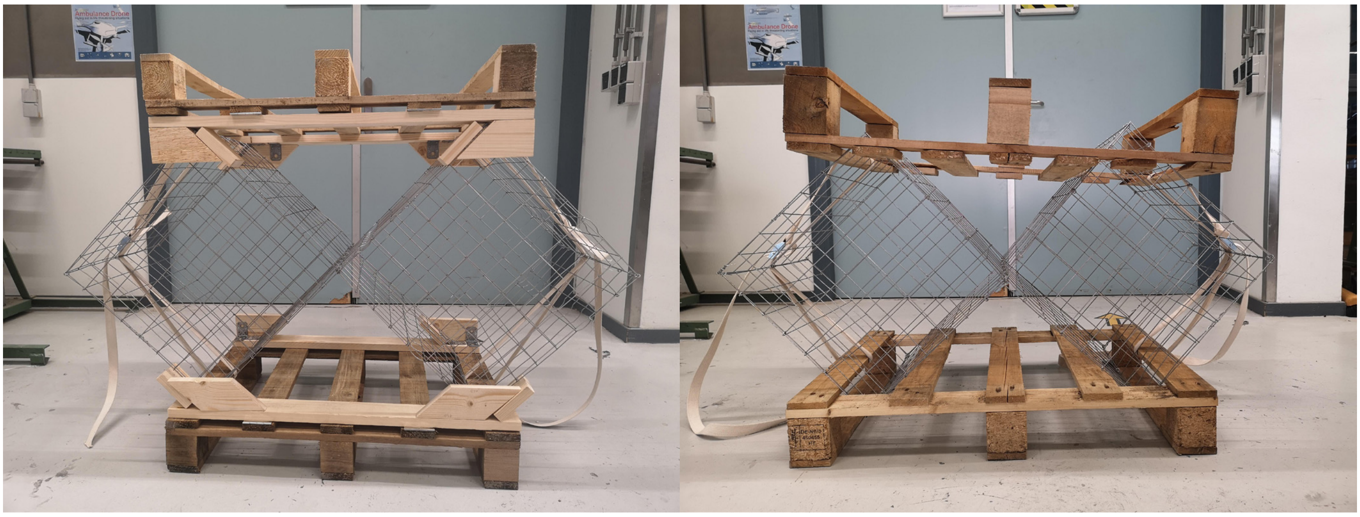


Figure 71: Two different design ideas for using pallets with the gabions. A – gabions with additional barriers, B – gabions fitting into the pallet gaps.

4.4.3 Gabions on pallets – structural integrity tests

Regarding the design iterations for gabions on pallets, two possible design ideas have been developed (Figure 71).

One with additional barriers screwed to the two edges of a pallet (Figure 71, A), which can hold two 108l (440x440x550mm) gabions in a double diamond shape and prevent them from sliding off. Barriers can rotate to flatten the pallet when it is being transported, this saves space, improves stacking, and reduces the probability of breaking.

These additional structures allow various types of display pallets to be used in deployment, enabling more opportunities for using used pallets.

Another design is simplified, where two smaller 70.4l gabions (400x400x440mm) are fit into the gaps of the display pallet and another pallet is added on the top (Figure 71, B). After everything is tightened together with a rope around, gabions are secured and cannot slide off from the pallets. The structure is much simpler, but only certain types of pallets can be used for the assembly adding some challenges for sourcing used pallets from various locations.

Figure 72: Assembly A before the test. After oyster shells were added, gabions' dimensions were distorted, and gabions became shorter. This resulted in gabions sliding off one of the edges.

Figure 73: Assembly A during the test. Assembly was knocked down sideways to imitate an accident on the deck or the moment when the unit hits the water surface. Both gabions fall off the top barriers.

Figure 74: Design 1 after the test. It can be seen, that the corners have been broken through mesh weldment points revealing sharp wires.

Each concept had different advantages and disadvantages, therefore, final testing with the added weight of oyster shells was planned to compare and evaluate structural integrity while simulating stresses which could arise during the handling and deployment phase.

Testing & insights

During the tests with added oyster shells, it was clear that the design with additional barriers introduced many challenges. Firstly, added oyster shells distort gabion dimensions, they became shorter than 550mm, easily slid off the barrier part (Figure 72) and become unstable. To keep gabions stable, the length of gabion baskets should be increased but then empty gabions would not fit into the assembly. Secondly, when the unit was dropped to one of the sides (imitating an accident on the deck or the moment when the unit hits the water surface) (Figure 73), the whole assembly was damaged, with gabion falling completely off one of the barriers, revealing how fragile the correct setup is. Thirdly, the impacts and stresses were concentrated mostly on the gabion corners, which led to them breaking in welded points, revealing sharp metal wires, which would pose safety concerns (Figure 74).

Conversely, the second design has performed much better in terms of structural integrity and handling. Firstly, smaller gabion sizes (70l) were much easier to handle compared to 110l ones, they are more lightweight and easier to carry by 2 people. Secondly, when gabions were fitted into the gaps (Figure 75), the majority of the stress for the mesh was divided more evenly on a larger area and the corners (top and bottom) were more protected. In addition, if the lashing is passed through the gabion mesh, stress is also better distributed in the mesh frame when the structure needs to be tightened together. Lastly, the assembly was rotated and flipped around multiple times (Figure 76) after which neither assembly nor the gabions were severely damaged (Figure 77).

Figure 75: Assembly B before the test.

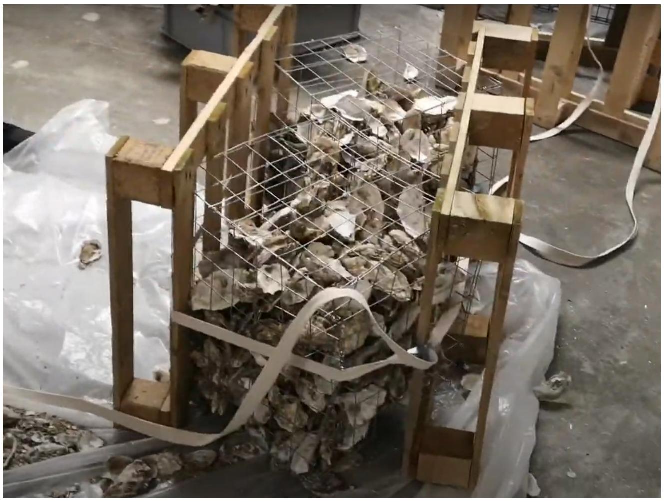


Figure 76: Assembly B during the test. Gabions stay securely placed between the pallet gaps.

Figure 77: Assembly B after the test. No significant damages were recorded.

Outcome

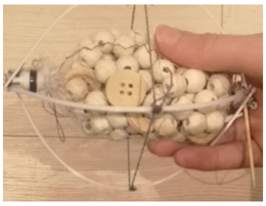
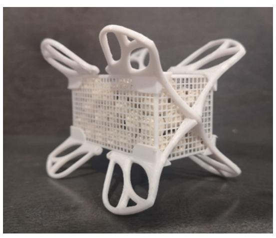
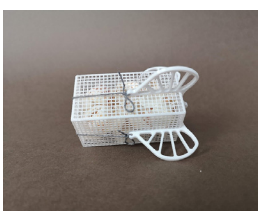
This test has shown that a simplified assembly does not only require fewer materials but also has better structural integrity, which is a crucial point for an offshore deployment environment, where assembly and preparations will be done fast and include the heavy weight of the oyster shells. Therefore, Assembly B is a superior solution over the design with barriers and will be chosen as the final solution for this concept.

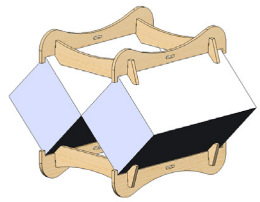
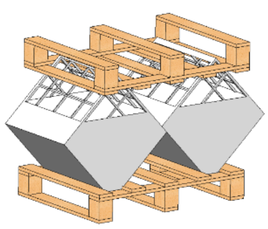
4.4 Advantages & disadvantages

With multiple conceptualization and prototyping iterations, each concept could be analyzed to find their prospective advantages and disadvantages from multiple perspectives: scalability, manufacturing, possible deployment scenario, and risk of sedimentation on the seafloor. Table 10 provides a summary of these findings.

Table 10: 6 concepts. Their advantages and disadvantages.

Concept	Advantages	Disadvantages
1. **Oyster nets with a rigid frame** 	• **Frames are lightweight and easy to assemble:** the frame is divided into two parts which surround and squeeze the oyster bag. Teeth introduced in the last iteration provide the best grip and stability. • **Efficient use of space:** all frames can be stacked on top of each other to save space during transportation. Without the frame, units with oyster shells also are space efficient in the hatchery or during transportation.	• **Complicated and expensive frame manufacturing:** if frames would be laser cut, a lot of material would be lost. If frames would be made from steel beams and welded, the point welding and bending process would be complicated, expensive and result in heavy structures. • **Frames inhibit sliding:** due to their attachment method, the frames are perpendicular to the sliding direction of the whole oyster bag row. Therefore, sliding this assembly from the deck would not be a suitable method. Unrolling or specific deployment structures would need to be built to facilitate easier deployment. • The hexagonal frame shape saves some material use compared to the rectangular shape. However**, the assembly is less stable underwater** and if currents are perpendicular to the assembly row, it could start rolling. • **Narrow frame edge can get buried in the sand quickly.** This will reduce the distance between the bags and the sand floor but stabilize the structure from rolling away.

	Advantages	Disadvantages
2. Oyster nets with unfolding frames 	• **Idea has the potential to become a fully automated** oyster deployment solution with a human intervention needed only to assemble the frame ends and to check deployment procedure quality. This would greatly improve deployment speed. • With most preparation work done on land, **much fewer personnel are needed on the vessel** itself, which will reduce deployment costs.	• **Mechanism is complex and would be produced with injection moulding, in the best case from biodegradable plastic**. Injection moulding only makes sense in large-scale production. For medium-scale production, the costs of manufacturing would be too expensive to make it a viable solution. • **Unclear how to manage the balance between frame beam stiffness:** the beams should be stiff enough to raise the oyster bag from the sea floor, but also flexible enough to be winded up around it. In the current prototype, the beams are not stiff enough to raise the structure from the surface but can be twisted around quite easily. • **Large winded-up structures can be dangerous for people around them.** similar to numerous large and loaded springs, these structures can unfold with great force and cause accidents if they do so in the wrong place and time.
3. Gabion basket with corner supports 	• **Efficient oyster protection from sedimentation:** structure raises all oysters above the 20cm sedimentation line as defined in the design criteria. • **Will always fall into the right position** when deployed in a row. • **Structural stability** because gabion's corners are protected from impact.	• **Supports will be very expensive to manufacture.** Due to their more complex geometry, these supports will either need to be inject-moulded from bio-based plastic. Another possibility is to assemble these parts from cut parts, but that will introduce a lot of new assembly steps and manual labour costs. • **Supports are less space efficient.** Due to their geometry, the supports cannot be stacked as efficiently as with other concepts. This will use up precious space during transportation and on the ship deck. • **Assembly can become time-consuming.** With more assembly steps and more parts that need securing to the assembly, the time for deployment might become less efficient because preparing each unit will take a longer time, compared to other concepts.
4. Gabion basket with supports 	• **Material use is drastically reduced:** 4th iteration uses 68% less material than the initial concept with fewer manufacturing steps and easier assembly. • **Easy assembly on the ship deck or land**: The base is connected in a cross structure, and then the gabion is placed into the support. The gabion and support legs are tightened with a rope, the unit is rotated sideways and connected to another unit. • **Simple geometry with an interlocking mechanism** does not require using other fastening equipment or tools for support assembly. • Structures are designed in a way to **facilitate easy sliding on the deck** in the longitudinal direction.	• **16%-20% of oysters would be lost if the latest support design is used**, compared to 0% with supports fixated on the corners from Chapter 3. Supports would need to be enlarged drastically to further reduce oyster loss. • **Structures are complicated and expensive to manufacture**, especially when using non-toxic material possibilities. • Tests have shown that for structures to fall in an upright position, more distance between the modules is needed – more ropes, more possibilities for entanglement and possible danger on the deck.

	Advantages	Disadvantages
5. Two gabions between CNC frames 	• **Assembly is quick and simple.** Frames are assembled from 4 parts each. Then two gabions are placed into the designated grooves and connected together. • **Effective oyster protection and high survival rate.** The frame protects gabions from impact and deformation during the deployment and raises them 140 mm from the ground which results in an improved oyster survival rate (97.7% above the 200 mm sedimentation line). • **Structure is deemed more stable in comparison to a single unit.** It is wider and will resist stronger water currents without tilting. Surface complexity is enhanced because two gabions introduce the bottom hole, several corners, and gaps between each module, where various fish and other marine organisms can grow and live.	• **Part geometry is complex and expensive to manufacture.** For this complex geometry, CNC would be the method of manufacturing. Plywood is usually used for CNC manufacturing, but due to chemicals used even in formaldehyde-free types, it is not a suitable material to be left to decay in the marine environment. Therefore, these parts could be made with CNC from untreated solid wood planks, but the whole process becomes more expensive due to more manual labour needed in the preparation stage and more expensive material. It would cost around 50 euros per part (according to the quotes from the manufacturing facility in Amsterdam). • **Bumps designed to restrict gabions from sliding off might be too weak** and could break off during the deployment, because of the wood fiber direction and gabions will slide off the assembly. • When exposed to damp or weather dynamics environments, **untreated wood parts tend to deform non-uniformly, making the frame fit less predictable**. • **Unit may fall in three positions (*Figure 56*):** upright – in that case, 97,7% of oysters are above the sedimentation line, sideways – 79,7%, which **decreases the survival rate**. Further testing should be done to determine what is the possibility the structure lands sideways. If there is not enough tension on the line between the units, they might also fall on the front or back, which would further increase the number of oysters getting sedimented.
6. Two Gabions between pallets. 	• **Structure is deemed more stable** in comparison to a single unit - it is wider and will resist stronger water currents without tilting. • **Durability:** Designed to endure the rough handling process, euro pallets can be used with loads of up to 500kg (half-pallets – 250 kg). • **Affordability:** Standardized pallets are used in almost every larger-scale logistics operation, the manufacturing process is highly automated, therefore the costs are relatively low: from 10 to 15 euros per pallet. • **High availability:** As a standard, euro pallets are manufactured across Europe and used interchangeably. Pallets can be acquired from local warehouses or businesses reducing the need for long-distance transportation. • **Circularity:** Various companies that focus on euro pallet repair. If necessary precautions are considered, used pallets can be deployed with this assembly as well. The main point of attention would be to ensure that they are not chemically contaminated. • **Surface complexity:** Pallets with double diamond gabion position have a relatively complex geometry with many corners, cavities, and holes for various marine species to settle.	• **Unit may fall in three positions**: same risk of the whole unit falling sideways as with concept with CNC frames (*Figure 56*), which decreases the oyster survival rate (97,3% survival if unit falls in a desired upright position, 84,3% survival if unit falls sideways). If there is not enough tension on the line between the units, they might also fall on the front or back, which would further increase the number of oysters getting sedimented.

4.5 Final evaluation

After ideating on chosen ideas from the system map, prototyping and testing some of them out, collected insights could provide a strong basis for idea evaluation. Concepts were evaluated according to design criteria (Chapter 2, Table 4), and design evaluations were illustrated with a Decision matrix from the Whole Systems Mapping method (Figure 78).

Regarding oyster survival, most of the concepts effectively support oyster survival by using nature strategies to protect them from predation. Single gabion with corner supports outperforms most of the concepts because it provides effective protection against sedimentation by raising them 20cm above the seafloor. In addition, a single gabion size will provide an effective waterflow through all oysters. 2 gabions connected on the CNC frame and on the Pallets raise oysters up to 10 cm, which introduces minimal risks of bottom oysters getting sedimented. The waterflow for gabions on pallets is more efficient than gabions on CNC frames or with one-sided support because the hole in the pallets allow more current to go through and reduce the probability of areas where there is no nutrient intake in the gabions. Nets with unfolding frames performed the worst because, in the last prototype, the frame beams were not strong enough to lift the bag from the ground, while making them stronger resulted in the winding mechanism not being able to work.

In terms of scalability, the concept with pallets performs best because it employs standard and widely available elements, which reduces the price, assembly is quick and easy, and no special tools are needed for deployment. On the contrary, Gabion with corner frames and Nets with unfolding structures would be much more expensive to make, both needing injection moulding, which would require to use of (bio-based) plastic materials, such as PHA or PHB which degrade in a marine environment very slowly. CNC frame also did not perform well in terms of price because the manufacturing method is expensive, and each part will need to be milled from solid wood planks – this process may increase the price up to 50 euro/part.

Regarding the stability on the seafloor, 2 gabions connected together offer the greatest stability due to their increased surface. These structures are more stable and larger, thus, more easily located with sonar which can save time during monitoring. Both concepts with nets underperform in terms of stability because the frames are more circular and will be more prone to rolling once introduced to a stronger waterflow.

In terms of handling and deployment, the design with pallets outperformed the rest of the concepts, mainly because of its simple assembly and minimum number of steps needed for it. However, this concept has 2 possible positions – upright (the correct one with minimal oyster

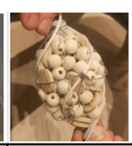
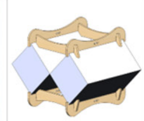
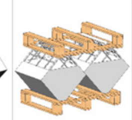
							
Objective	**Weight**	**Nets with a rigid frame**	**Nets with unfolding frame**	**Single gabion corner supports**	**Single gabion one side support**	**2 gabions with CNC frames**	**2 gabions with pallets**
Protection from sedimentation	**5**	4	2	5	3	4	4
Protection from predation	**5**	3	3	4	4	4	4
Effective water flow	**5**	4	4	4	3	3	4
Low price	**5**	2	1	1	2	2	5
Fast deployment	**5**	3	5	2	3	3	4
Withstanding bottom currents	**4**	1	2	3	3	4	4
Micro-habitats	**2**	2	2	3	4	5	5
Minimal care to fall in right position	**4**	5	5	5	5	3	3
Lightweight (pre-assembly)	**2**	2	2	3	3	4	4
Integration into the hatchery	**3**	5	3	3	3	4	5
Possibility to locate	**2**	2	3	3	3	4	4
Minimal need to retrieve	**4**	4	3	4	4	5	5
	Total Score	**147**	**138**	**155**	**152**	**166**	**194**

Figure 78: Decision matrix evaluating 6 concepts according to design criteria.

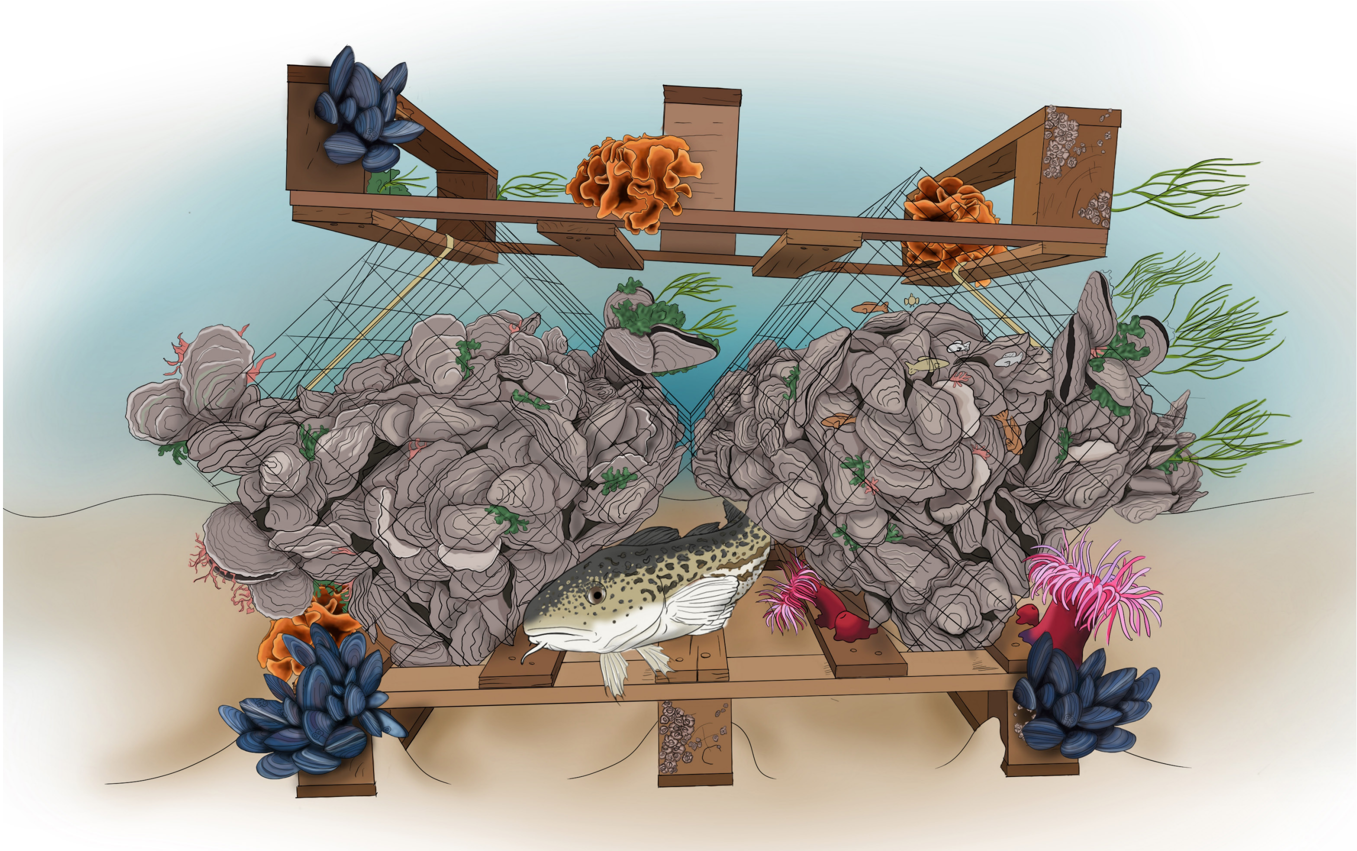
sedimentation) and sideways (if the structure falls on one of its sides – then oyster sedimentation risk increases). The concept with a CNC frame has the same challenge. On the contrary, most of the other concepts are designed to fall in multiple positions without compromising oyster survivability.

According to the decision matrix and considerations mentioned previously, the idea of assembling gabions on the pellets is the most promising one and will be developed for the detailed model.

CHAPTER 5:
FINAL DESIGN

5.1 Oyster survival
5.2 Scalability
5.3 Broader ecological success
5.4 Handling & Deployment
5.5 Final design evaluation

Ilustration showing how the designed units can provide suitable habitat for multiple marine species.



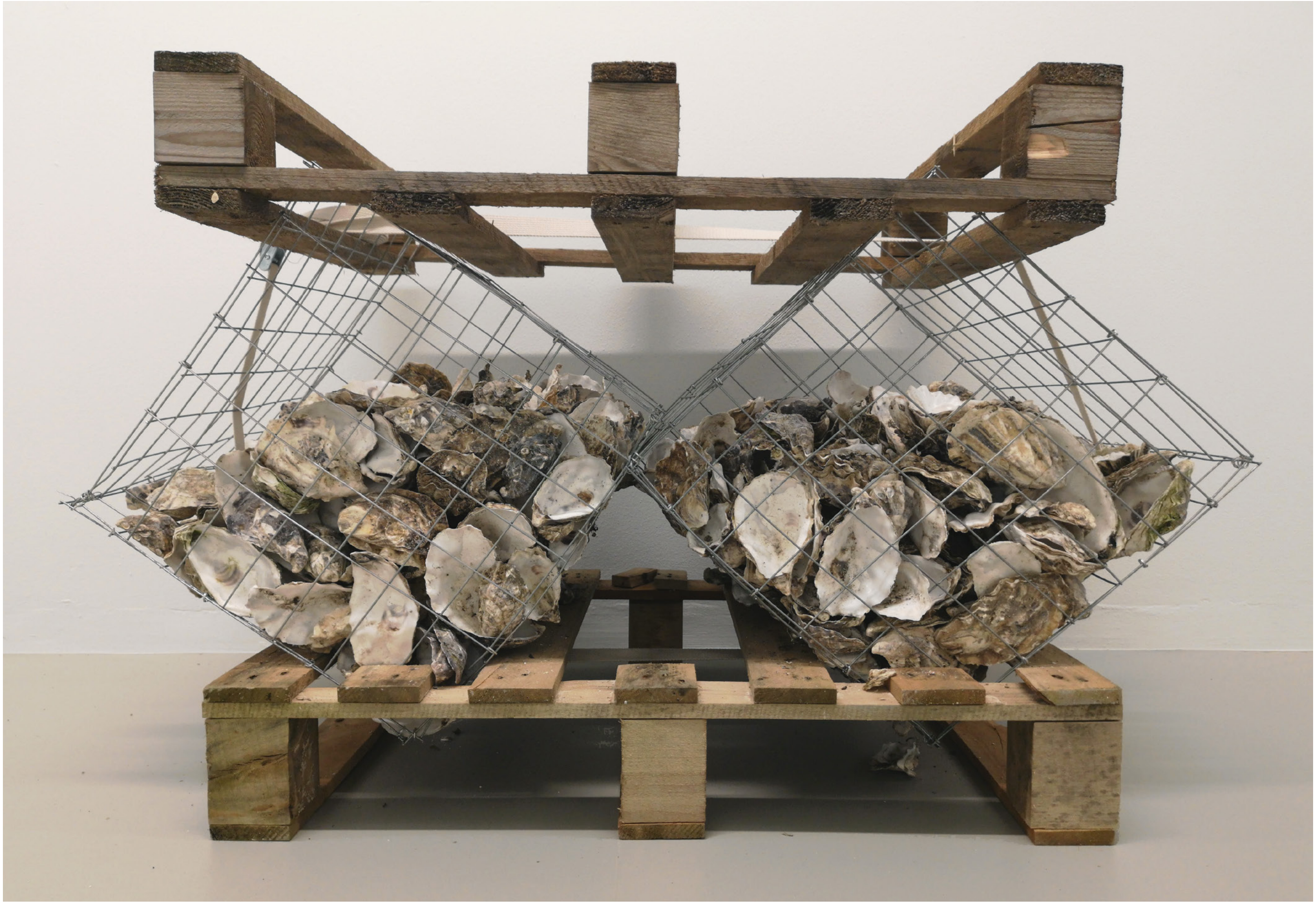


Figure 79: An assembled unit with empty oyster shells.

In this chapter, detailed design is described using 4 categories: oyster survival, broader ecological success, scalability, and handling & deployment. In comparison, to previously discussed solutions (for details, see Chapter 2) final design is more scalable for larger offshore marine restoration areas due to cheaper construction and faster deployment times. The construction maintains a better balance between the oyster survival criteria and introduces a variety of shapes and materials which can provide shelter for a broader range of benthic marine species. The structure consists of natural (wood and natural fibre ropes) or non-toxic biodegradable materials (steel mesh) – which is why it can be left to degrade on the ocean floor without harming the ecosystem.

5.1 Oyster survival

On the sea floor, each unit creates a favourable environment for the spat on shell to grow inside and offers protection from various environmental factors.

5.1.1 Protecting from predation

Shells packed together already provide a lot of protection because for predators, such as starfish and crabs, it is more challenging to access them. In addition, steel mesh introduces a second barrier for larger predators to access oysters.

Figure 80: Packed oyster shells and steel mesh create some protective barriers for predators.

5.1.2 Protecting from sedimentation

The dimensions for the gabion basket were set as 400x400x440 mm to fit between the pallet gaps, with an inner volume of 70l. To provide some space for young oysters to grow, gabions would be filled by 80% to 90% of the full volume capacity resulting in 56l to 63l of oyster shells in each gabion. Additional space in the basket will provide space for young oysters to grow and is preferred over filling the basket completely. Therefore, each unit with 2 gabions houses 112 l to 126 l of spat on shell.

As defined in context analysis and design criteria (Chapter 2, Table 4), sand mega-ripples can reach up to 20cm in height and sediment oysters. With this design, gabions are in a double diamond shape with their bottom edges raised from the seafloor by 7 cm. This results in 87% of oyster shells located above the theoretical sedimentation line (Figure 81) which would increase oyster survival.

In addition, the base for the pallets is hollow which increases and creates irregular flow below the structures which will impact the sedimentation patterns. Taking into consideration that the main waterflow direction changes 4 times per day according to high and low tides, some areas which get sedimented on one part of the day might erode later once the current changes to the opposite direction.

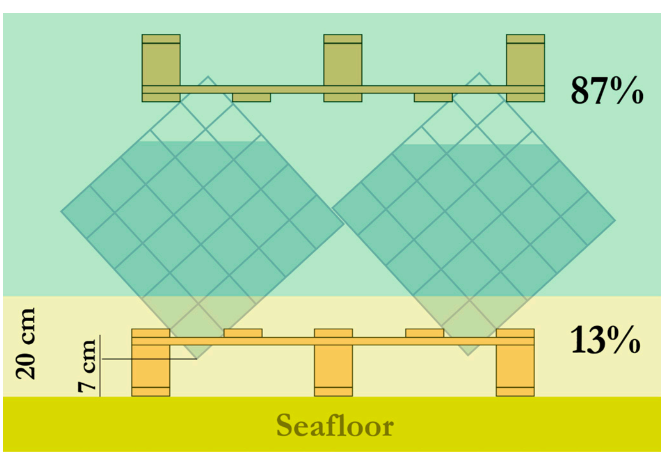


Figure 81: Theoretical calculations on possible sedimentation caused by sand mega-ripples. The plain yellow zone marks the possible sedimentation part (12% oysters in this zone), pale green – sediment-free zone (88% oysters above sedimentation).

To analyse how waterflow affects the seafloor, Solidworks CFD Flow Simulation was used. Firstly, a simplified true-scale assembly was modelled (Figure 82) with oysters being represented as a solid block to save computation time. Then, the Flow Simulation was used to calculate how geometry affects the velocity and direction of the current coming from one side. The parameters were chosen as follows:

Simulation results were presented in a cut plot which was made 1mm above the plane representing the seabed. A cut plot shows the contours for different speed zones and vectors for waterflow directions (Figure 83). Another simulation was done with a slower waterflow velocity, 0.8 m/s, and the same plot was created (Figure 84).

Table 11: Parameters for flow simulation in position A.

Fluid:	Water
Temperature:	282.15 K
Velocity:	X direction – 1.2 m/s, Y direction – 0 m/s, Z direction – 0 m/s

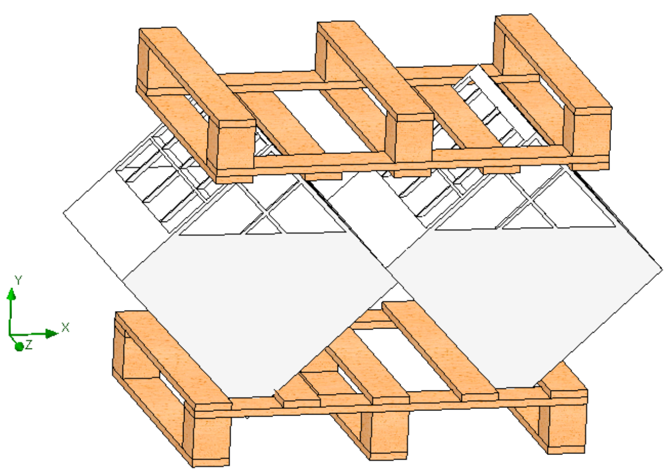


Figure 82: A simplified scale model of the structure.

From both cut plots, it can be seen that different speeds result in a very similar flow pattern. Vortices can be seen on the edges of the pallet legs and behind the corners at the very end of the structure (largest blue areas in both plots). The first left part of the pallet gap marks the area with higher speeds than the surrounding area because due to the slanting gabion's geometry, the water is guided downwards and channelled through the pallet gap. Once it hits the seafloor, the current slows down.

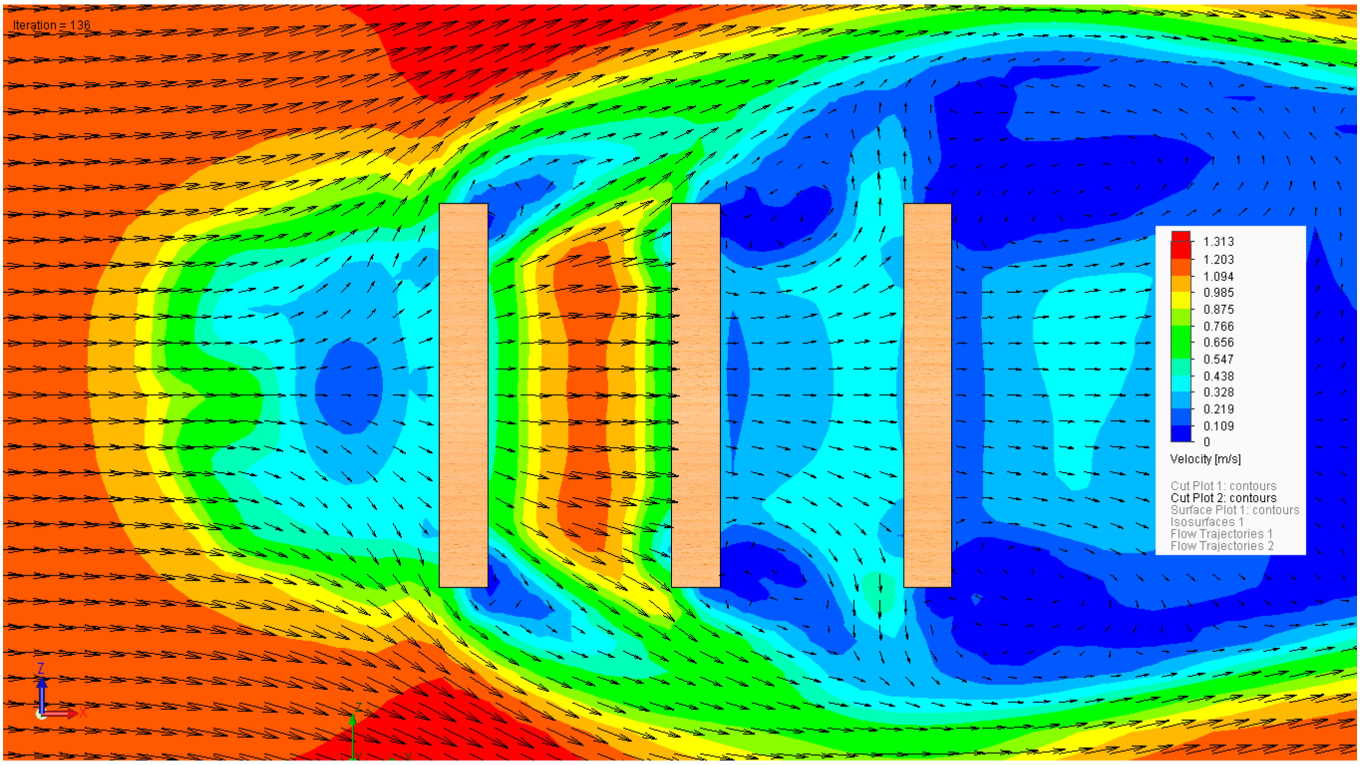


Figure 83: Cut plot of 1mm above the seafloor from Solidworks Flow Simulation, showing waterflow speed and direction is distributed. Starting waterflow speed = 1.2 m/s (marked in orange). The slowest zones, where sedimentation is most likely to occur are marked in blue. View from the bottom.

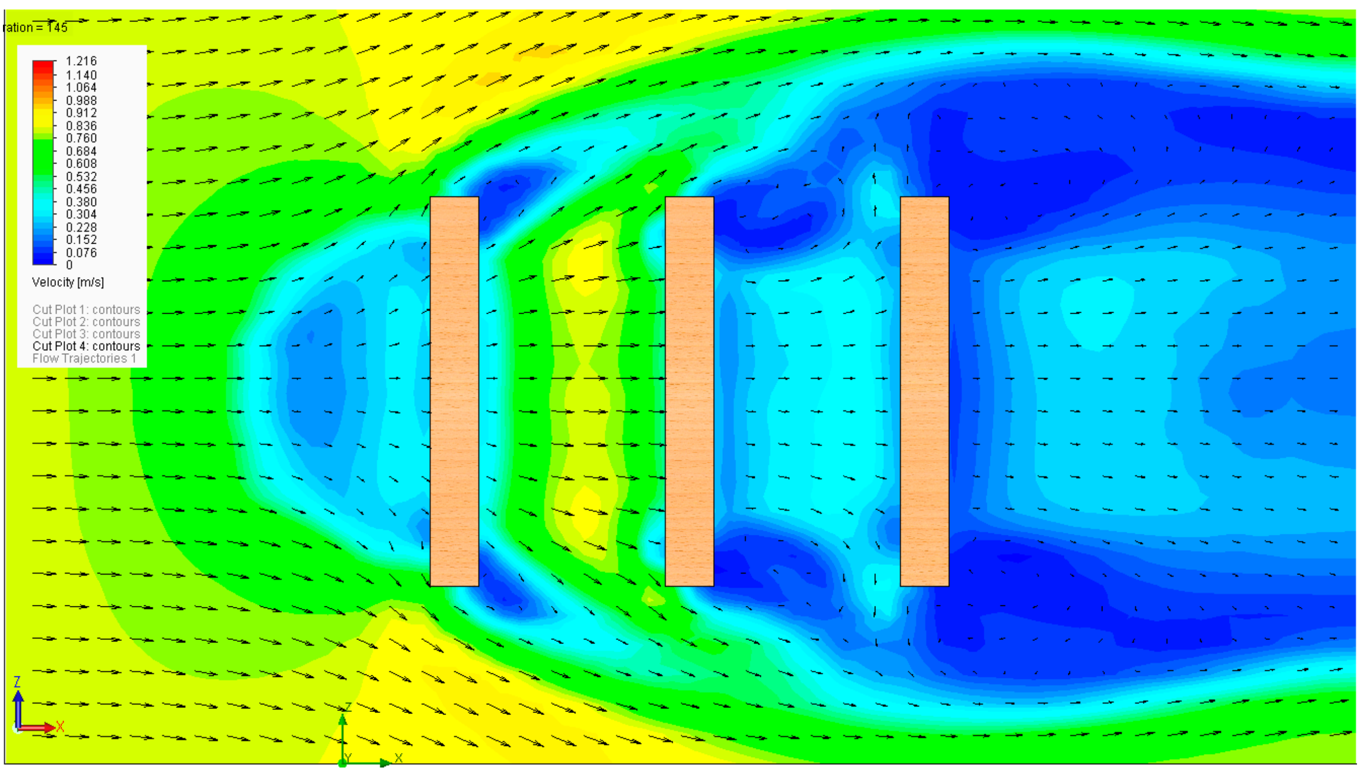


Figure 84: Cut plot of 1mm above the seafloor from Solidworks Flow Simulation, showing waterflow speed and direction is distributed. Starting waterflow speed = 0.8 m/s (marked in yellow). The slowest zones, where sedimentation is most likely to occur are marked in blue. View from the bottom.

Due to the tide, the water current goes in both directions, and some of the blue areas where sedimentations might occur would be cancelled out by the opposite current of high velocity - 'temporary sedimentation areas'. To see if there are any 'permanent sedimentation areas', where waterflow in both tide directions is slow and close to 0, a cut plot of 0.8 m/s (Figure 84) was copied, reflected vertically and positioned over the original plot with a 'multiply' overlay (Figure 85). In this way, areas that cancel out once the waterflow direction changes are marked in green because blue and yellow plots overlay and everything that remains in a similar velocity stays the same colour as the original plot (Figure 84). From this, it can be stated that, during both tide directions, zones in blue will remain slow waterflow zones where sedimentation will most likely occur. Sedimentation will likely occur on the sides, where the gabion geometry is higher and may sediment fewer oysters than expected.

This is a theoretical calculation with an even seafloor and without counting on the already accumulated sand. Therefore, it can only be used to assume possible accumulation tendencies. This phenomenon likely occurred due to the waterflow meeting the barrier (gabion), thus, creating a place of high pressure and low waterflow velocity. When pressure builds and current speed slows down this is where sedimentation is most likely to occur. And it does not get eroded but is further sedimented because when the current approaches the structure from the opposite direction, all the high speed is slowed down by the structure, and only slow waterflow forms behind the unit, thus pushing sand to those areas.

Insights about possible sedimentation zones and the way sediment might accumulate were translated to a possible sedimentation scenario in Figure 86. Parts with the slowest water speed would get sedimented at the highest rate, while the area below the pallet would remain without drastic sedimentation due to the tide currents 'cancelling out' this sand accumulation. If the unit would get sedimented in this way, the bottom oysters could have a higher chance of surviving.

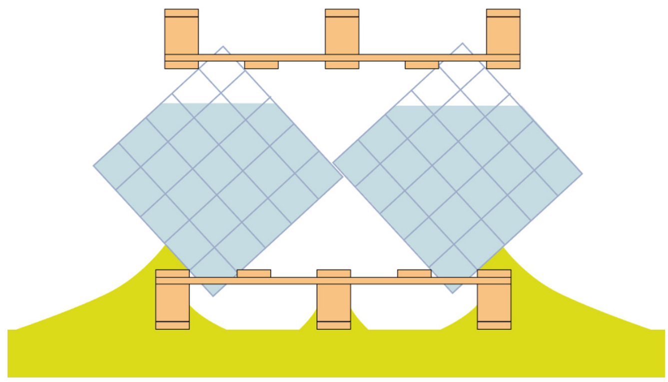


Figure 86: Insights from simulation translated to a possible sedimentation scenario.

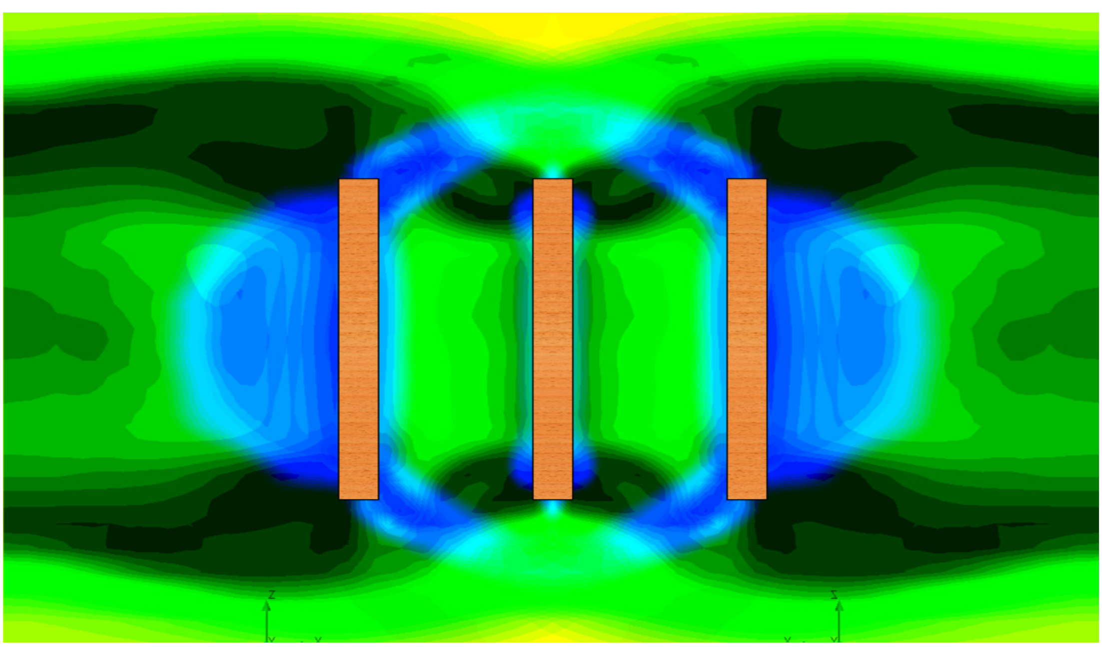


Figure 85: Two cut plots from flow analysis with a waterflow speed of 0.8 m/s are merged. The original plot was copied, reflected vertically and merged with original the one using a 'multiply' blending method. A pattern of 'permanent sedimentation zones'' emerges (marked in blue).

5.1.3 Gabion mesh size for oyster protection and growth

When using gabions for oyster restoration projects, some manufacturers advise using a welded steel wire mesh, with a 2mm wire diameter, because it ensures structural stability when baskets are being transported and deployed, thus, protecting the oysters from being crushed (EnZar, n.d.). According to experts from ARK, the most optimal mesh size is 40x40 mm, which is large enough to ensure the best water flow through oysters and minimize risks of hole clogging due to biotic growth around the walls, but at the same time is small enough to retain oyster shells inside the gabion. According to previous ARK testing experience, a mesh size of 50x50mm is already too large and some number of shells can be lost through the holes.

5.1.4 Gabion corrosion rate – providing enough space for adult oysters

Ideally, the structure protecting the oysters should degrade or disassemble on the seabed after 1 to 2 years to give adult oysters more space to grow. By that time oysters will have already hardened their shells and will be able to protect themselves from various predators.

Many gabions are made of steel wire which, if not protected, will corrode quite fast in contact with water or in a humid environment. While most industries would try to avoid this phenomenon, corrosion of gabion baskets is a desirable outcome in this project. Steel corrosion rate depends on many factors: steel grade, post-production processes and the chemical composition of the water the structure is put into. It is known that the average corrosion rate in The North Sea is from 0.83 mm of layer per year (for S355 steel) (according to Khodabux et al. (2020)) to 1 mm of layer per year (steel grade unknown) (according to experts at ARK). According to this calculation, using a 2 mm wire would take from 2 to 2.5 years to fully corrode.

5.1.4 Avoiding toxic steel mesh coating

It is a common practice for steel mesh gabions to be galvanized with zinc or coated with a PVC layer to protect them from corrosion and extend their lifetime, but when deployed underwater, that can cause negative effects on the marine ecosystem.

Zinc or Zinc Oxides can negatively affect various marine organisms (Sarker et al., 2021; Yung et al., 2014). Bivalves being filter-feeders are even more prone to the negative effects of Zinc: it accumulates in the soft tissue, inhibits growth, in increased concentrations can impact the population size structure by reducing the survival rate for young bivalves (Hanna et al., 2013). In addition, with the previous model from ARK, a galvanized steel mesh had very limited spat settlement in the hatchery. Therefore, a bare carbon steel mesh without any corrosion protection layers should be used for the gabions to limit the ecotoxicity in the marine environment and corrode in a desired timeframe.

5.2 Scalability

As discussed in chapter 2, the most challenging factor for scalability is the price. If unit production is expensive and deployment is slow, the solution will not be able to be scaled in terms of large area coverage. Here the cost estimation and deployment time are discussed.

5.2.1 Costs

Overall costs of one unit are calculated taking into account the materials, spat on shell and transportation deployment (Table 12). Each category is divided into more detailed costs. Materials, Oysters and Transportation are calculated for a single unit. When deploying spat on shell, Deployment is calculated per 1m^3 of oyster because units will because a single deployment chain will be at least 1m^3. Costs for 1m^3 of spat on shell with and without deployment are calculated for further scenario cost calculation.

Table 12: Cost calculation for unit preparation, transportation and deployment.

Gabions on pallets

Units needed for 1m3, pcs	8.36
Price of 1 unit, eur	1071.78
Price for 1m^3, eur	9055.36
Price for 1m^3 with deployment, eur	11531.85

All volume, l	**Filling, %**	**Oyster volume, l**
140.8	0.85	119.68

Material	**Quantity, pcs**	**Price per piece**	**Price, eur**	**Notes**	
Display pallets	2	10	20		Overall 72.45
Rope for assembly (50 m)	0.1	19.5	1.95	5m used	
Buckles (25mm)	1	1	1		
Steel mesh (4.5 m2)	0.3	165	49.5	Piece is 4.5 m2	

Oysters	**Quantity, l**	**Price per l**	**Price, eur**	**Notes**	
Spat on shell	119.68	8	957.44		Overall 957.44

Transportation*	**Price/m^3 of oysters**	**Price/unit, eur**	**Notes**	
Empty oyster shells (restaurant - hatchery)	50	5.98	Estimation	Overall 41.89
Spat on shell (hatchery - the port)	200	23.94	Estimation with preparation time	
Pallets & lashings (sorting centre - port)	100	11.97	Estimation	

Deployment costs for 1m3	**Quantity**	**Price**	**Price/1m3 oysters, eur**	**Notes**	
Vessel rent and staff costs	1	12000	2400	22hrs for 5m3	Overall 2476.49
Leading rope (50m)	1	19.5	19.5		
Anchor (7 kg)	1	56.99	56.99		

Unit costs

According to the calculation in Table 12, it costs 1072 eur to manufacture the structure and breed spat on shell for one unit.

Construction material price calculations were done according to the small-scale material prices during the prototyping phase, but with increased material amounts the construction price may go down. The high spat on shell cost is related to the fact that the hatcheries are still in the process of scaling up their production and success rates of producing spat on shell vary greatly. It is expected that the costs will go down once the large-scale spat on shell production takes place and the success rates are more stable. Regarding the empty oyster shells, ARK has already established partnerships with some oyster restaurants which provide oyster shells for free. If larger amounts are needed, more restaurants could be invited to take part and help with shells.

Deployment costs (1m^3)

With each unit housing 112l to 126l of spat on shell, 8-9 units will be needed to deploy 1m^3 of spat on shell to the sea. For each 1m^3, deployment costs are calculated in (Table 12, deployment costs).

Calculations considered ARK's plans to deploy 5m^3 of spat on shell in an offshore site, which can be considered as a small-scale deployment. Most of the costs go to vessel rent, crew and staff expenses which may cost from 10000 to 12000 euros for one day. If more units are deployed in a single journey, costs per 1m3 of deployment will go down.

5.2.2 Deployment time

The deployment costs are mostly based on operation time. The approximate time for deploying 5m^3 of spat on shell is calculated when the vessel sails from Ijmuden port to Hollandse Kust (West) offshore windmill farm area and back (Table 13).

Table 13: Deployment operations, tasks and activities with the time required.

Hours needed	Activities
6	Mobilisation, loading oysters and other materials for the units to the vessel, boarding.
5	Sailing: Ijmuiden (port) to Hollandse Kust (west).
6.25	Deployment of 5 m^3 of oysters.
5	Sailing: Hollandse Kust (west) to Ijmuiden (port).
22 hours	**Overall time needed**

Deployment time can be divided into separate tasks (Table 14). Unit assembly time approximation was based on experiences while testing the assembly (Chapter 4.4.3 "Gabions on pallets – structural integrity tests"). According to this calculation, deploying 1 m^3 of spat on shell will take 60 minutes. Additional 25% of the time (15 mins) was added for unexpected delays in the deployment process resulting in 75 mins needed to deploy 1m^3.

5.2.3 Overall costs for restoring one reef

Different sources state that to have a self-sustaining reef, it needs 60 000 adult oysters. According to calculations in the hatchery, each 1m^3 contains 1mln. spat on shell. New units can house 120l of spat on shell resulting in around 120000 spat in each unit. Previous field tests have shown that usually, Flat oysters deployed for restoration have a very low survival rate: just 0.4% of all spat on shell survive to adulthood. The newly designed units have not been tested in a field experiment yet and it is not possible to determine what the oyster survival rate will be when using them. Therefore, three different scenarios regarding oyster survivability were considered:

1. Pessimistic: design intervention has not improved oyster survival and survival remains the same as in previous field tests with only 0.4% of spat surviving to adulthood. In that case, 15mln. spat on shell or 15 m^3 should be deployed in a 3-year timeframe with 125 units. Every year, 5 m^3 should be deployed with 41-42 units.

2. Neutral: design interventions of oyster protection had a positive impact on oyster survivability and increased it to 1%. In this case, 6mln. or 6 m^3 of spat on shell should be deployed in a 3-year timeframe with 50 units. Every year, 2 m^3 should be deployed with 16-17 units.

3. Optimistic: design intervention has significantly improved oyster survival to 5% surviving to adulthood. In this case, 1.2mln. or 1.2 m^3 of spat on shell should be deployed in a 3-year timeframe with 10 units. Every year, 0.4 m^3 should be deployed with 3-4 units.

Table 14: Time needed for the deployment of m3 of oysters.

Type of Activity	**Time per unit**	**Time per 1m^3 (9 units total)**
Single unit assembly	5 mins	45 mins
Connecting all units with a lead rope	1 min	9 mins
Tying a lead rope to the anchor	-	1 min
Deployment into the sea	0.5 min	5 mins
Unexpected delays	-	15 mins

Table 15: Price calculation for each scenario, total and yearly.

Units needed for 1m3, pcs	8.36
Price of 1 unit, eur	1071.78
Price for 1m^3, eur	8955.36
Price for deployment 5m^3	12000

Scenarios	Spat on shell, total m^3	Units needed, total pcs	Spat on shell, m^3/year	Unit needed, pcs/year	Deployment, eur/year	Unit & deployment, eur total	Unit & deployment, eur/year
Pessimistic (survival 0.4%):	15	125	5	41 - 42	12000	**170330.46**	**56776.82**
Neutral (survival 1%):	6	50	2	16 - 17	9960	**83612.19**	**27870.73**
Optimistic (survival 5%):	1.2	10	0.4	3 - 4	9000	**37746.44**	**12582.15**

When calculating costs for these scenarios, decreasing the required spat volume reduces overall unit costs but only partially reduces deployment costs because majority of the time is spent on mobilisation and sailing. In the Neutral scenario, deployment costs are reduced by 17% compared to the pessimistic one, in the positive scenario – reduced by 25%.
Taking these considerations into account the costs for each scenario are calculated in Table 15.

Drastic price decrease with increased survivability in Table 15 is related to the reduced amount of spat on shell that is needed to restore one self-sustaining reef. Table 12 shows that the spat on shell comprises 89% of the whole unit price, therefore, if these required volumes can be decreased, the price will drop drastically.

5.3 Broader ecological success

5.3.1 Withstanding high-speed currents

From the initial site analysis in (Chapter 2), it is known that there are two dominant water current directions impacted by high and low tides and other less pronounced directions. In extreme events, current speeds can reach up to 1.2 m/s, therefore, it is important to analyse how this maximum waterflow speed can affect structural stability. The assumption is that when the structure is parallel to the waterflow (Figure 87, A) the force will try to lift the unit's bottom left edge, but the unit will remain in a stable position due to its gravitational force. If the structure is perpendicular to the waterflow (Figure 87, B), due to a less streamlined geometry, waterflow will lift the unit's front edge with a greater force than the gravitational force making it unstable.

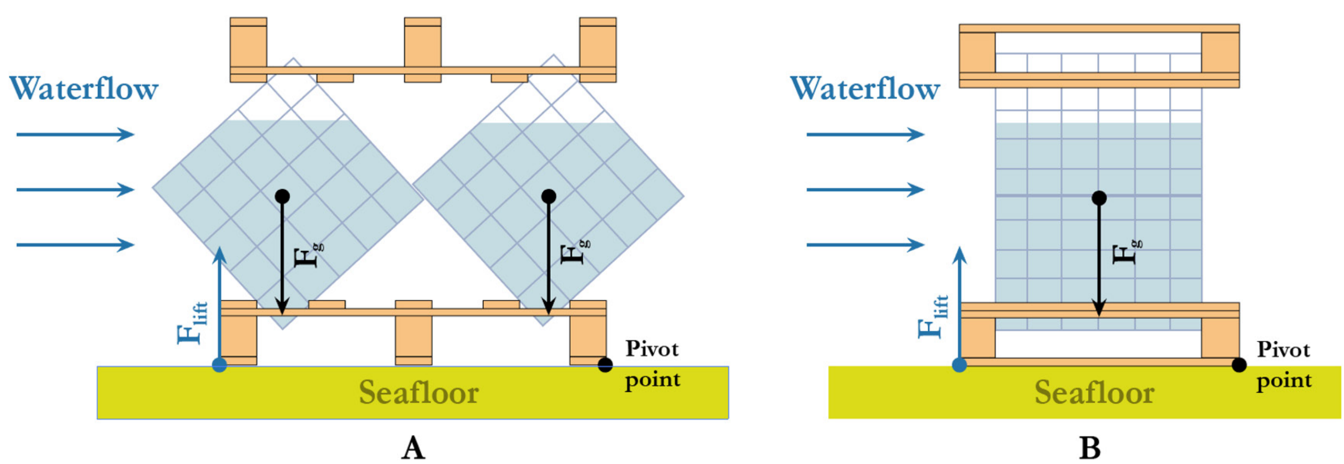


Figure 87: Two positions against the waterflow: A - when the unit is parallel to the waterflow, the water current will lift the bottom left edge with a certain force. B - when the unit is perpendicular to the waterflow, the current will lift the front edge with a certain force.

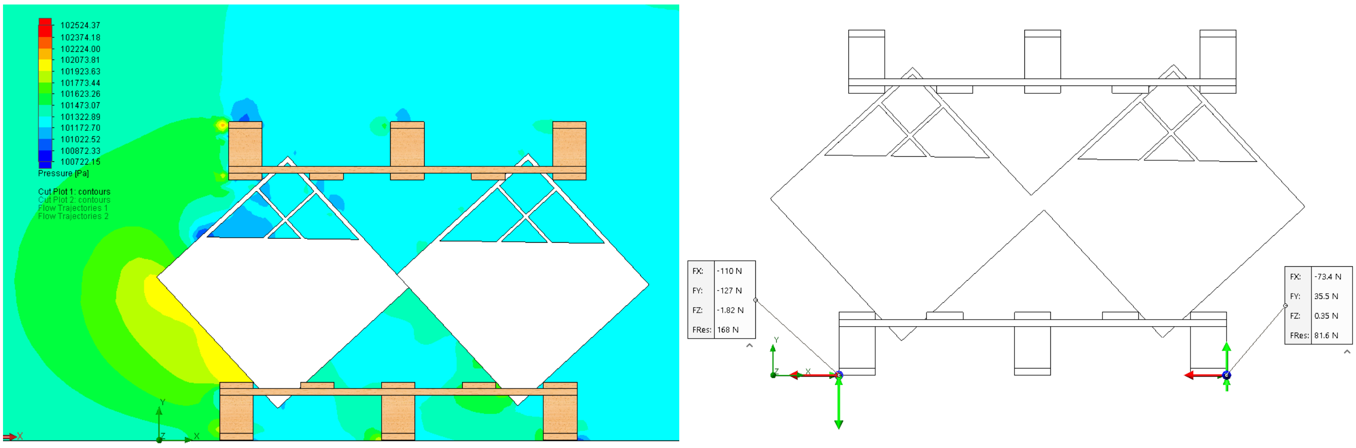


Figure 88: Calculated Fluid pressure from SOLIDWORKS Flow analysis is translated to reaction forces in static analysis to calculate with what force the current will lift the left side of the unit. Left – Flow simulation results – cut plot in the middle of the structure, right – Static simulation results showing the reaction forces.

To calculate how waterflow impacts the stability in each position, two types of SOLIDWORKS simulations were used: CFD Flow Simulation and FEA Static Simulation.

For the Flow Simulation in position A, the same full-scale model (Figure 82) and the same parameters (Table 11) were used as previously. The simulation then calculated where the fluid pressure would build up (Figure 88, left). These results were then imported to FEA Static Simulation to calculate the forces on the bottom left and right edges. The whole assembly was made rigid to prevent deformation, bottom left and right edges were fixated to prevent any movement. The simulation calculated the reaction forces (Figure 88, right) which were translated to the lift force created by waterflow: F_{lift} = 127 N force, 35.5 N force downwards on the right bottom edge (due to the whole pressure build-up, the bottom right edge is pushed downwards) was not used for further calculations.

Gravitational force (F_g) for each of the gabion weight centers was found with Solidworks geometry calculations and subtracting the buoyancy force mostly occurring from the wooden pallets. Assembly is symmetric, therefore, each gabion weight center acts in downward force of F = 137.45 N. Forces are then translated to the moments (Table 16).

Table 16: Position A. Forces are translated to the moments.

F_{lift}:	F_{lift} = 127N
F_g:	F_g = 137.45 N
M_{lift}:	M_{lift} = 127 N · 0.8 m = 101.6 N·m
M_g:	M_g = 137.45 · 0.67 m + 137.45 · 0.13 m = 109.95 N·m
M_{final}	M_g - M_{lift} = 109.95 - 101.6 = 8.35 N·m (downwards)

M_{lift} is lifting the bottom left edge with 101.6 N·m while the moment of gravitational force is around 109.95 N·m. The position is theoretically stable, but this is already a boundary condition, and some units could be flipped by this strong current. Then again, if units are placed quite a while before the extreme current event, some part of the bottom pallet will get sedimented and both wooden pallets will absorb water, therefore, reducing the buoyancy force. These two factors would stabilise the structure further and minimize the possibility of it being displaced or rotated.

The same approach was taken to calculate when units are in position B – perpendicular to the waterflow (Figure 87, B). In this case, for Flow Simulation, water velocity was set to 1.2 m/s in the Y direction, and 0 m/s in other directions. The calculated fluid pressure (Figure 89, left) was translated to Static simulation where reaction forces were found (Figure 89, right) and were translated to waterflow forces acting on the front bottom edges (F_{lift}). The gravitation force for the whole assembly was left the same and moments were calculated (Table 17).

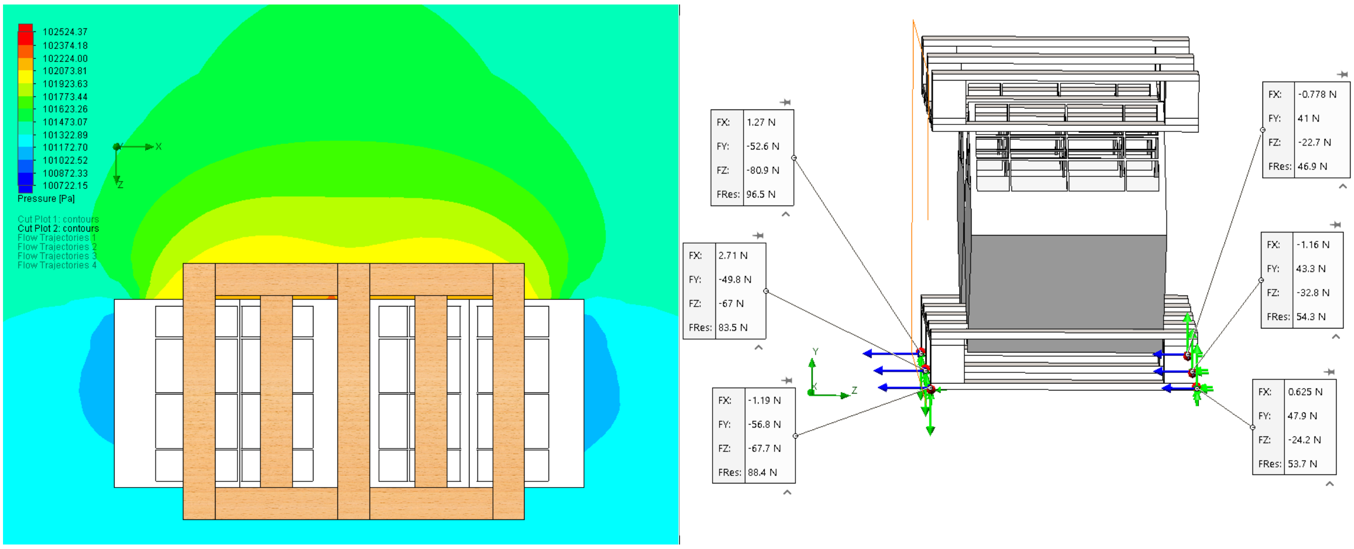


Figure 89: Calculated Fluid pressure from SOLIDWORKS Flow analysis is translated to reaction forces in static analysis to calculate with what force the current will lift the front side of the unit. Left – Flow simulation results – top view of cut plot in the middle of the structure, right – Static simulation results showing the reaction forces on each of the bottom edges in front and back of the pallet.

According to Table 17 the Moment of gravitation force is smaller than the moment that lifts the front edge. This means that in this waterflow speed when the structure is perpendicular to the dominant tide currents it may become unstable and flip over.

Overall, the structure is highly likely to maintain a stable position when it is positioned parallel to the dominant currents (Figure 87, A) even in the highest waterflow with a velocity of 1.2 m/s. If units are positioned perpendicular to the main tide directions (Figure 87, B) they may become unstable when the waterflow is at its highest velocity. Therefore, when deploying, units should be positioned parallel to the dominant tide current directions.

Table 17: Position B. Forces are translated to the moments.

F_{lift}:	F_{lift} = 159.2N
F_g:	F_g = 274.9 N
M_{lift}:	M_{lift} = 159.2 N · 0.6 m = 95.52 N·m
M_g:	M_g = 274.9 · 0.3 m = 82.47 N·m
M_{final}	M_{lift} - M_g = 95.52 - 82.47 = 13.05 N·m (upwards)

5.3.2 Micro-habitats

With their varied geometry, units may also create places with varied water velocities, creating a prerequisite for other benthic organisms to grow on the units or hide in the gaps from predators or high waterflow. To see how geometry impacts waterflow direction and speed, calculation results from the Flow Simulation for sedimentation were used (Table 11). A cut plot in the middle of the structure (Figure 90) showed that multiple vortices form where gabions are connected to each other and where the left gabion connects to the pallet. In addition, the top pallet creates turbulence which also introduces vortices and slows the waterflow down. Part of the waterflow is channelled through the holes of the bottom pallet, where the speed increases.

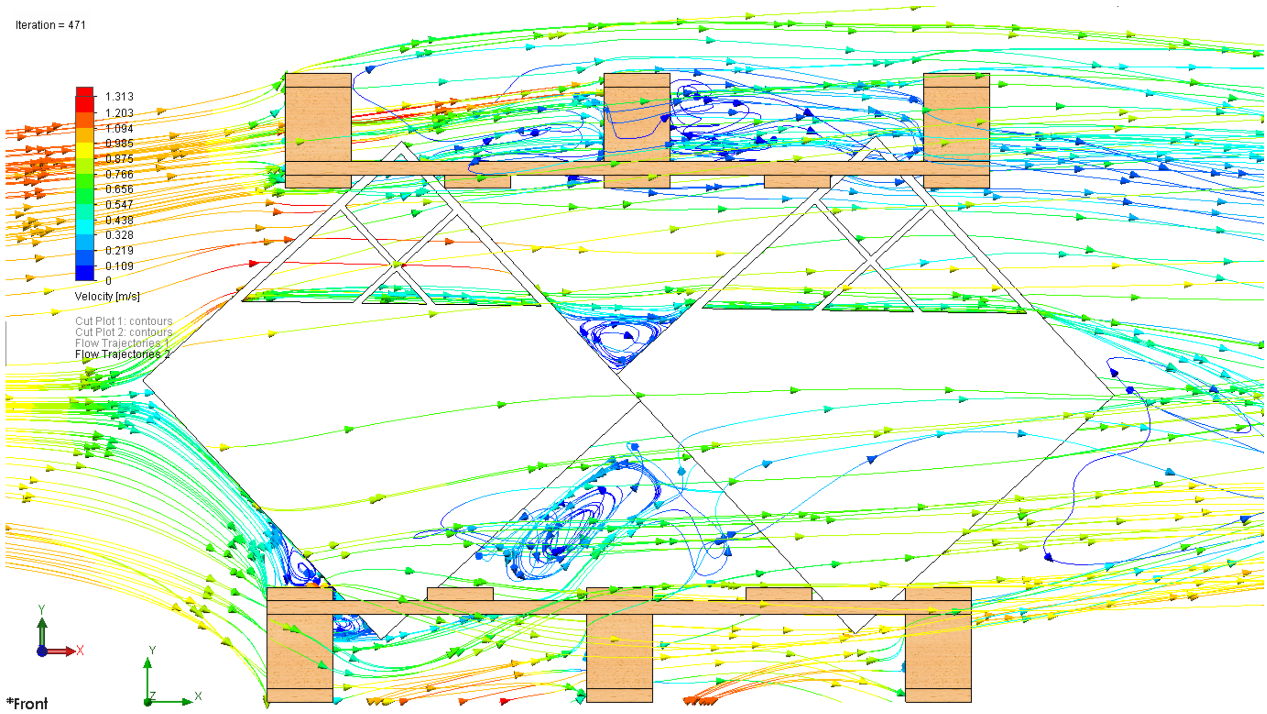


Figure 90: SOLIDWORKS Flow analysis for position A. A simplified model showing how structure impacts the dominant water current direction and speed: Red colour indicates the highest current speed (1.3m/s) and blue - slowest speed (0 - 0.1 m/s). Multiple refuges from high-speed currents are created.

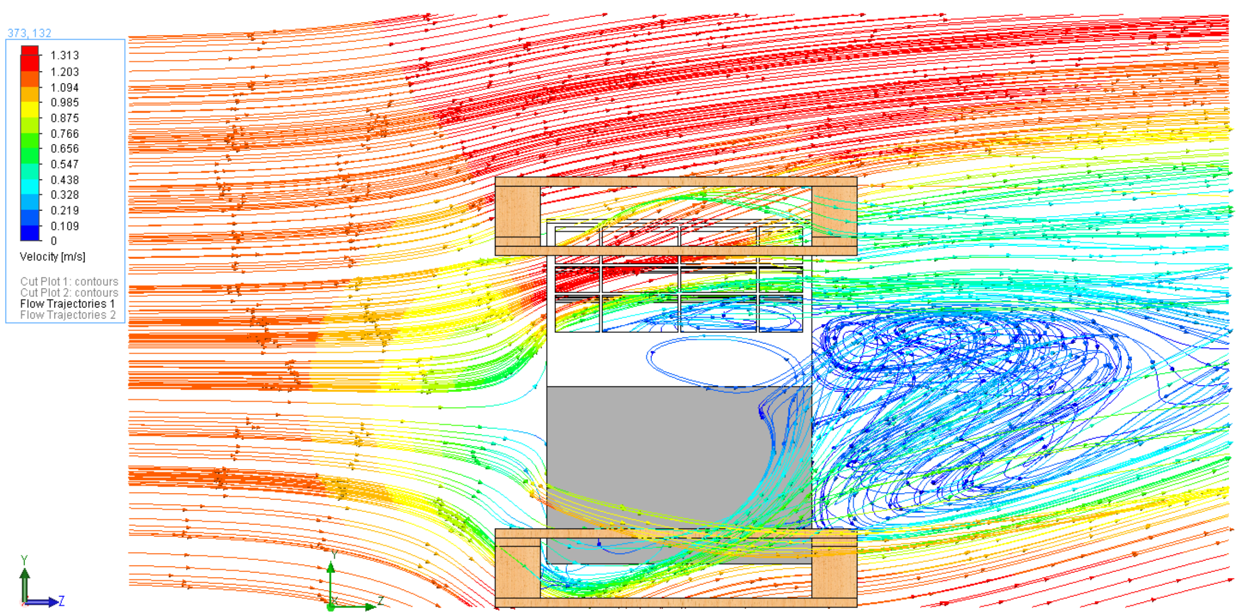


Figure 91: SOLIDWORKS Flow analysis for position B. A simplified model showing how structure impacts the dominant water current direction and speed: Red colour indicates the highest current speed (1.3m/s) and blue - slowest speed (0 - 0.1 m/s).

When the gabion was positioned perpendicular to the same current speed (Figure 91), the results have shown that fewer microhabitats would be created because waterflow does not slow down that much, and the main vortices form behind the unit.

In addition, different materials also offer varied mediums for other benthic species to settle (Figure 92). For example, wooden pallets, similar to shipwrecks, can provide a hard substrate for barnacles, mussels, various types of sponges, shrimps, sea anemones and fungi (Sea Ranger Service, 2022; Rämä et al., 2014). Oyster shells can provide numerous cavities and gaps for microorganisms, juvenile fish or shrimp and many other small species. Gaps between two gabions can also provide a refuge for crabs, lobsters, and various types of juvenile or predatory fish, such as Atlantic cod (Lengkeek et al., 2013).

The desirable unit position is parallel to these dominant currents because it ensures structural stability on the sea floor and creates multiple micro-habitats with different current speeds (Figure 90) for various marine species on the pallets, between and inside the gabions (Figure 92).

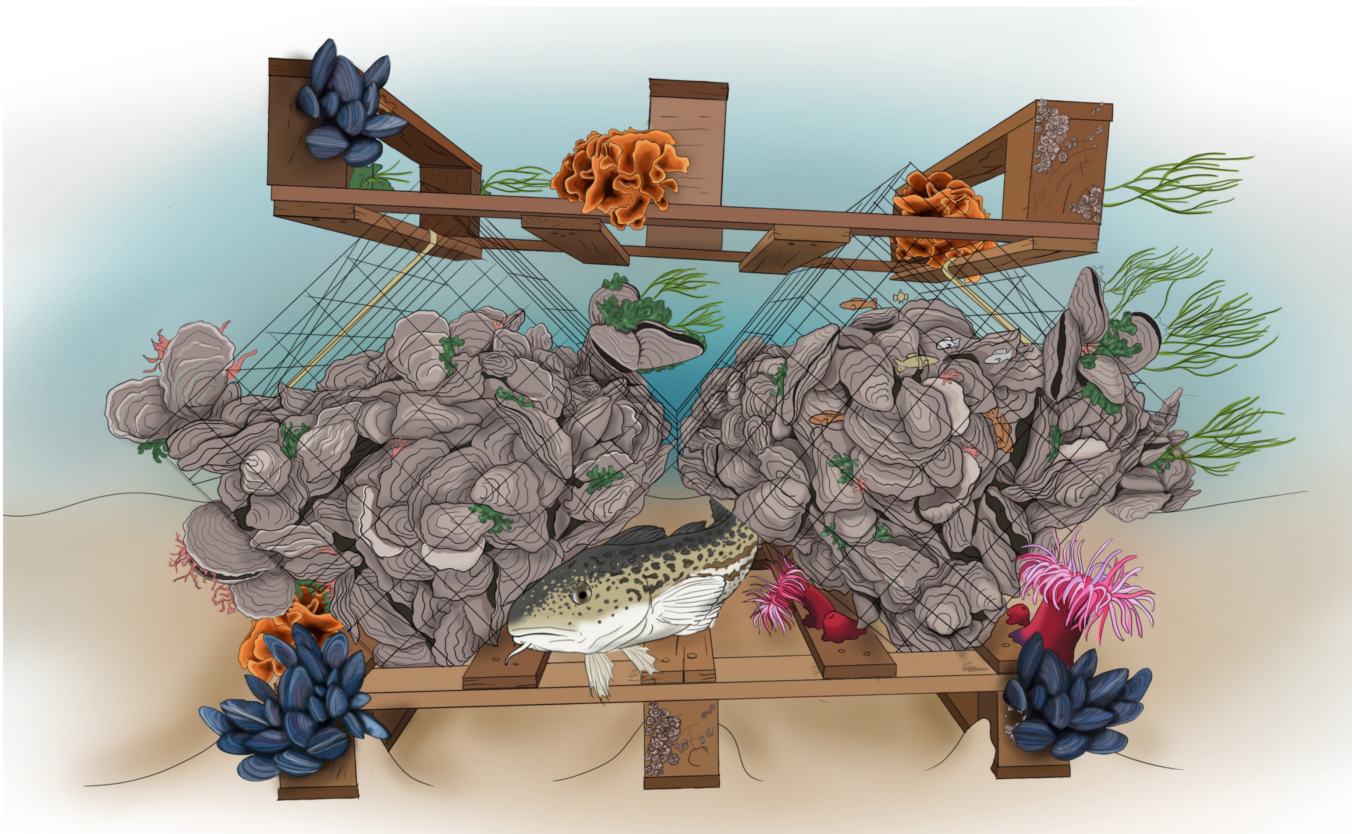


Figure 92: One unit can create a suitable habitat for multiple marine species, such as Atlantic Cod, Actinia, various marine plants and juvenile fish.

5.4 Handling & Deployment

5.4.1. Construction & Materials

General properties:

- Full assembly dimensions: 720x1100x600 mm
- Weight of the whole assembly: 76 kg
- Volume of oysters per one unit: 126l

One unit is built from these elements:

- **126 l of spat on shell** provided by the oyster hatchery, usually 1 or 2 months old.
- **2 lightweight display pallets**, with standard dimensions of 800x600 mm. While pallet dimensions are standard, board arrangements on the pallet may differ (see Figure 94) and should be made with a board arrangement that can fit the gabions between the gaps in the correct direction. Pallets can be sourced from various pallet recycling centers or bought from logistic centers. Sometimes the blocks are made of compressed wood fibers which should be avoided because they deteriorate in water quickly. Instead, pure wood blocks should be used. Pallets are usually heat-treated without using chemicals; this treatment type is often marked on the pallet as HT (discussed in Chapter 4).

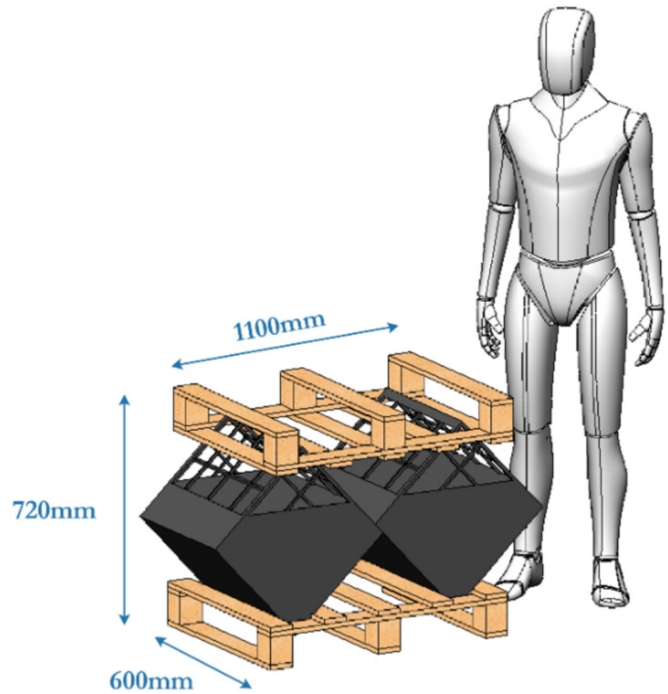


Figure 93: Assembly dimensions.

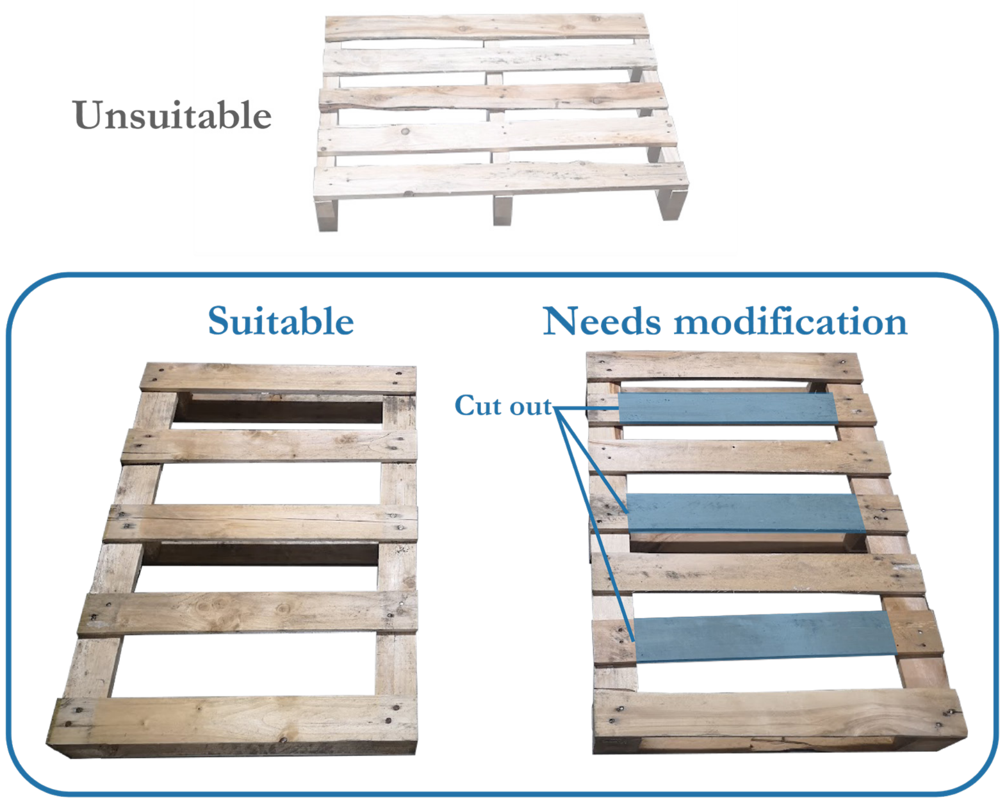


Figure 94: Various types of display pallet board arrangements, from which two are suitable.

- **2 gabions of dimensions 400x400x440 mm**, made of 40x40 mm square spot-welded steel mesh with 2 mm wire thickness. The 40x40mm mesh gap size is an optimal solution to retain the majority of oyster shells inside and ensure effective water flow through the oysters. The mesh is made of bare steel without surface treatment, which, after being deployed to the sea, will corrode in 2 years. By that time, oysters had grown enough to protect themselves from predation.
- **1 cotton lashing** (25mm), length of 3m, with a 25 mm cam buckle to tighten the assembly together. Another alternative is to use a natural jute/cotton rope only by tying it up with a taunt line hitch knot, which is a self-tightening knot. This would eliminate the need for a cam buckle.
- **1 leading rope**, length of 20m, which connects all units in a row. Ropes made of natural fiber, such as Sisal, or Manila are used for nautical activities. Sisal rope is heavier but more resistant to breaking down in salt water, which can be an advantage if the units need to stay arranged in a row for multiple years for monitoring.

5.4.2. Handling & assembly

While the whole unit assembly is done on a ship deck, some elements are integrated into the system earlier, and some are introduced at a later stage (Figure 95). Gabions will be constructed, filled with empty shells – up to 63l for each gabion, and put in the hatchery pools where young oysters will be grown on them. After one or two months the gabions will be taken out of the hatchery by hand, with ropes or with metal hooks. Due to the wet shells and new young oysters, each gabion will weigh around 35 kg and should be lifted by 2 people. Every 8 gabions will be placed into 1 IBC unit (Figure 96) and once all gabions

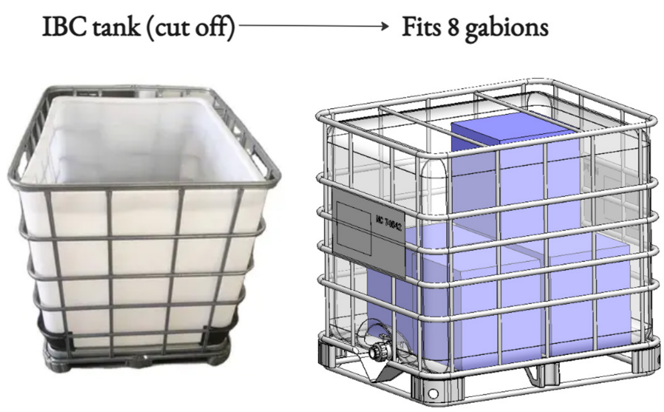


Figure 96: IBC tanks can be used to transport the gabions from the hatchery to the deployment site. Each tank can fit up to 8 gabions. Water can be filled up or drained according to necessary circumstances.

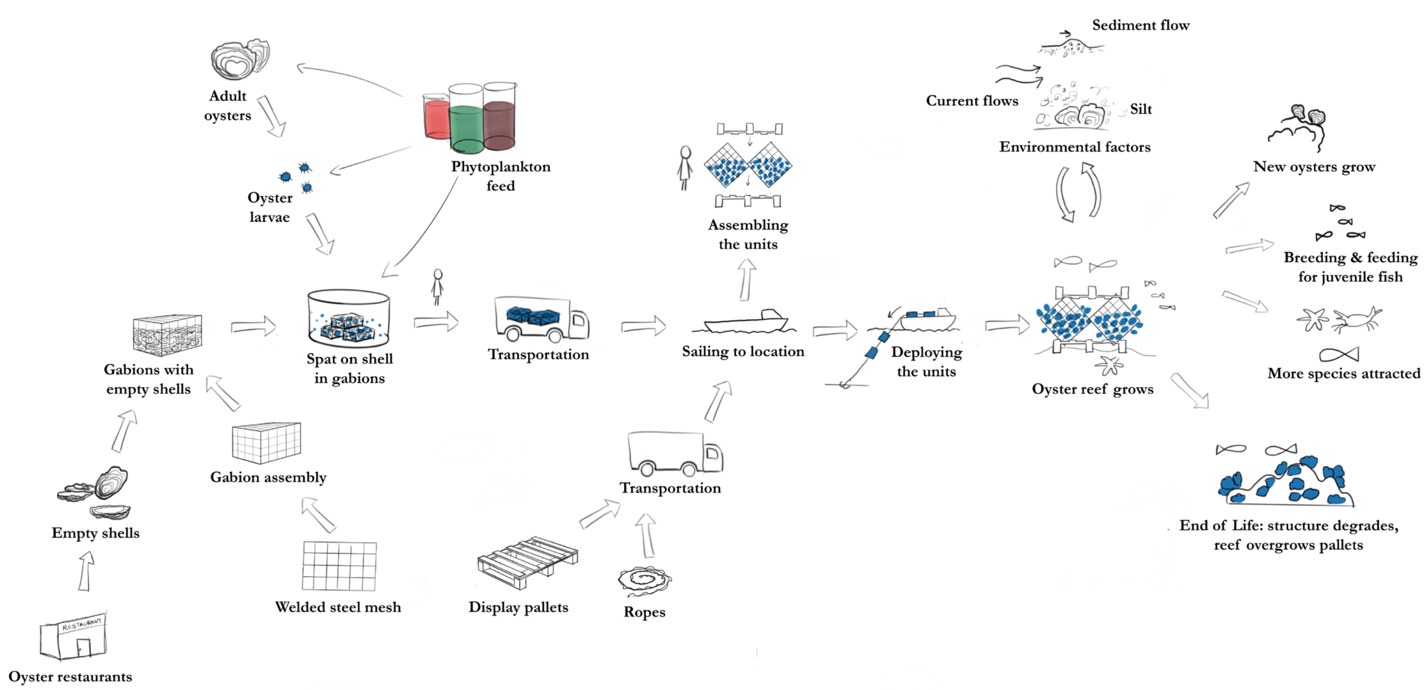


Figure 95: System map of the final design.

are fit they will be transported to the ship. Other materials for the assembly, such as display pallets and ropes are transported to the ship from a different location. While the ship is sailing towards a dedicated location, the units with oysters are assembled and prepared for deployment.

If the trip by ship is short, up to 8 hours, and there is no direct sunlight that day, oysters can stay without being submerged in the water, with some periods of hosing them with water. If the trip is longer, taking more than 8 hours or with direct sunlight, oysters need to be put into the water to prevent drying out. This will be done by filling up the IBC tanks with seawater while oysters are transported to the deployment site in the vessel. Right before the unit assembly task, IBC tanks will be drained to improve gabion deployment preparation tasks.

As the ship sails toward the deployment area, units are being assembled and arranged for deployment on the ship's deck. The unit is assembled in 5 simplified steps (Figure 79):

1. Place two gabions with oysters on the pallet in a double diamond position.
2. Fix the gabions together with two hog rings on each side.
3. Put on the top pallet. Put the lashing around the unit by puling it through the gabions and the pallet.
4. Tighten the assembly with a clam buckle.
5. Finished assembly.

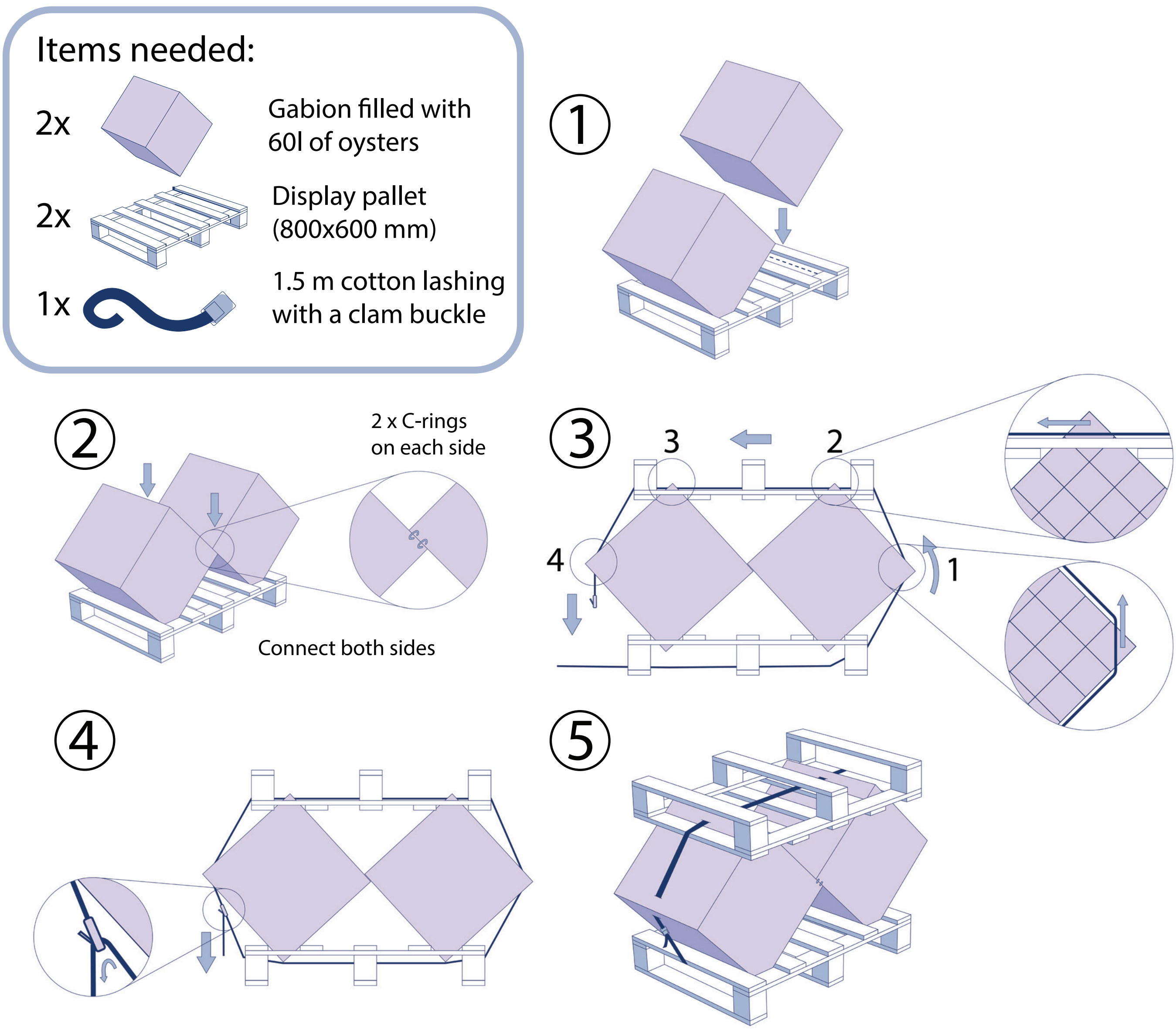


Figure 97: One unit assembly instructions.

5.4.3. Deployment

The units are arranged in a string and tightened with a continuous leading rope, with an anchor at the very beginning of the row. When the ship arrives at the desired location, the anchor is thrown overboard and while the ship is moving, it grabs onto the seafloor and starts pulling the units. Units slide off the deck one by one into the sea. To deploy 1 m^3 of oysters in a single chain, 8 to 9 units are needed, and more units can be attached to deploy a larger oyster volume with one anchor.

Figure 99: RV Pelagia. Photo credits: NIOZ, 2017.

To see how a deck arrangement could look like, ARK's plans to deploy 5m3 of spat on shell were taken into account. One of the suitable vessels for this type of deployment would be RV Pelagia owned by NIOZ (Figure 99), which is a marine research vessel with a clearance at the end of its deck where gabions can slide off into the sea. A plan for 5m3 spat on shell deployment on an 8x8m deck is planned accordingly (Figure 100): if gabions are filled at a maximum 90% capacity, 40 units will be needed to deploy this volume. For this, 80 gabions will be carried in 10 IBC units which will be located at the back and near the edges of the deck space to reduce the time for walking when assembling. During the assembly 10 oyster units can be connected together with a leading rope and an anchor in the middle of the deck. Gabions are carried for IBC units in the corner to the middle of the deck.

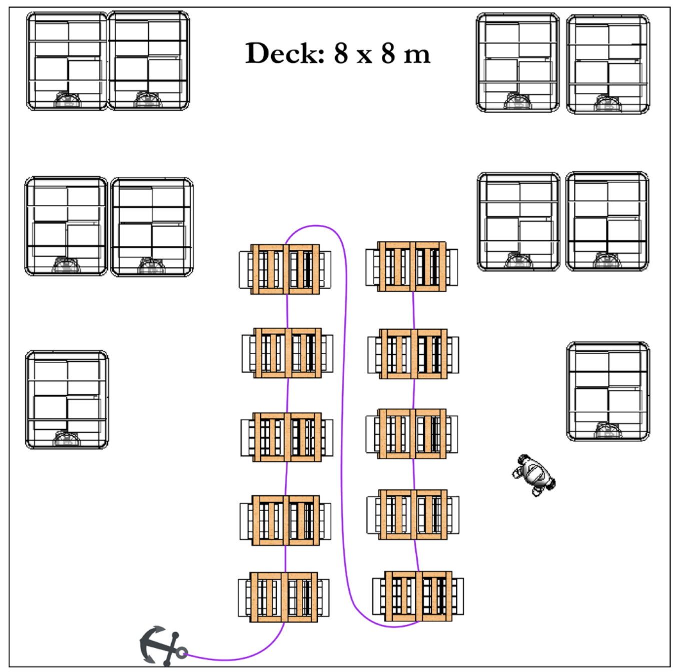


Figure 100: A plan for an 8 x 8 m deck. IBC units are located at the back and around the edges to minimize the distance needed to walk. In the middle 10 oyster units are prepared before the deployment, all connected with a leading rope (marked in purple) which is connected to an anchor.

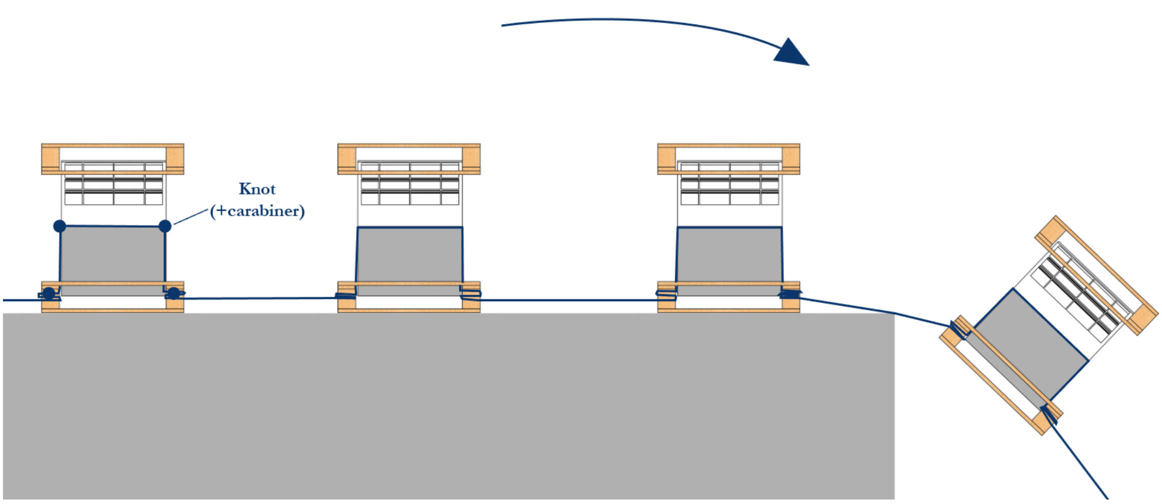


Figure 98: deployment scheme

5.5 Final design evaluation

Finally, the design is evaluated (Figure 23) according to previously collected design criteria (Chapter 2, Table 3) and requirements with in-depth explanations in Table 8.

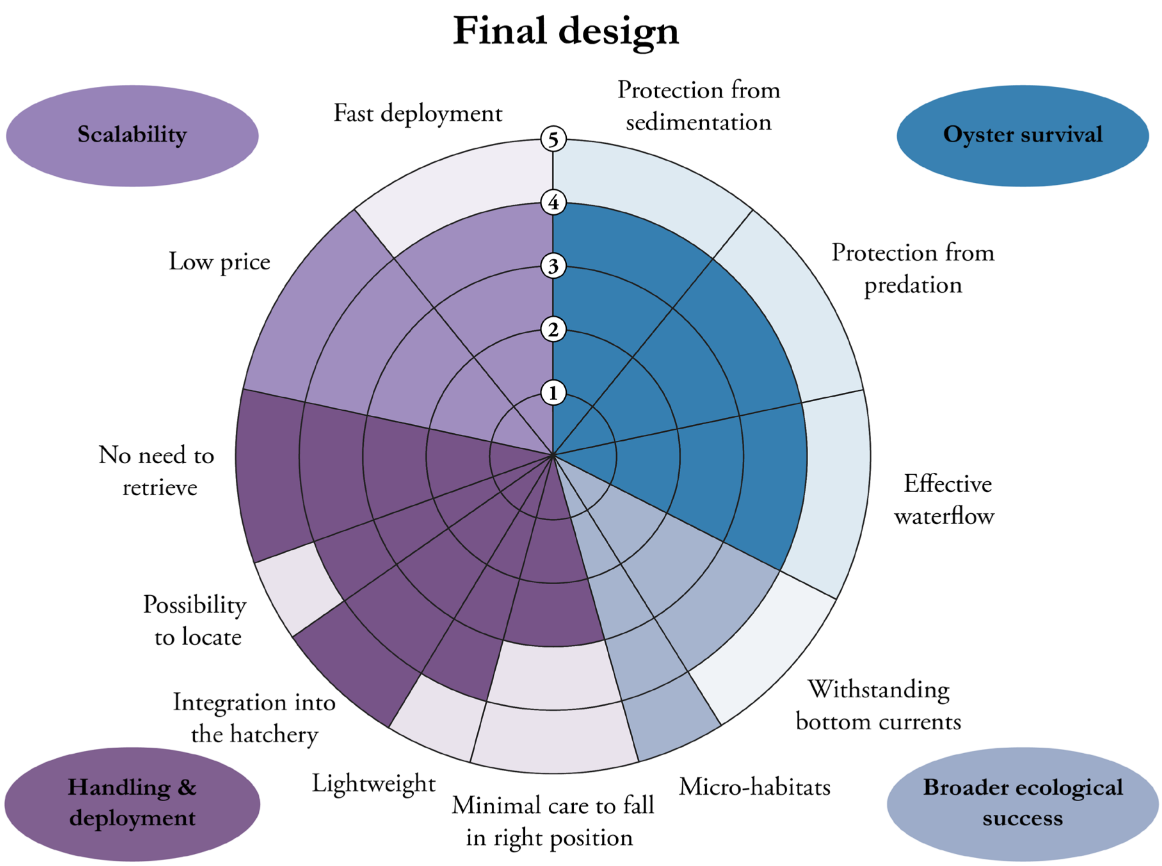


Figure 101: Evaluation of the final design according to multiple design criteria. The further from the center the dot is, the better evaluation. Dot size signifies the importance of that design criteria.

Table 18: Final design evaluation.

Criteria	Points given	Explanation
1. Protection from Sedimentation	4	With gabions placed on the pallet in a double diamond position, 87-90% of oysters are above the theoretical 20cm sedimentation line and should have a higher survival rate. In addition, according to Flow Simulation results, sediment would tend to accumulate around the unit and not below the gabions.
2. Protection from predation	4	Gaps between the shells offer effective protection for young oysters against the main predators such as crabs or starfish. At the same time, they will be able to grow in additional gabion space and, later on, around them. Oysters on the outside layer might be more susceptible to predation, but the inside ones will stay protected. Gabions are made of steel mesh which will rust away in 2 years, enabling adult oysters to grow further.
3. Effective waterflow	4	Metal mesh with 40x40 mm grid openings and 2mm wire provides large enough gaps for water to flow through and avoid being overgrown by marine organisms. Oyster filtration depends on the current speed, and the location where oysters are in the gabion: oysters in the outside layer will filter more water with nutrients, while oysters on the inside might receive less water flow and fewer nutrients. Openings in the pallet allow more current to flow under the construction and the oysters, reducing possible 'dead spots' with no nutrients.

Criteria	Points given	Explanation
4. Low price	5	Structure without spat on shell for each unit costs 78 euros, which is almost 8 times cheaper than producing 126l of spat on shell for each unit. With a larger scale, prices will go down for both elements: spat on shell production will become cheaper and, with increasing quantities, materials will become cheaper as well.
5. Fast deployment	4	At least 1 m^3 can be deployed using 1 anchor and 8 units. More units can be added to the same row to increase the deployed oyster volume with one anchor. 75 minutes are needed to prepare 8 units with $1m^3$ of spat on shell. Deployment does not use any additional heavy machinery making deployment safer and faster.
6. Withstanding bottom currents	4	Solidworks Simulations have shown that when units are placed parallel to the dominant waterflow directions, they maintain a stable position even at the maximum current speed. If structures are placed perpendicular to the main tide current directions, there is a chance they can be tilted.
7. Micro-habitats	5	When placed parallel to the dominant waterflow directions, each unit creates various micro-habitats and a refuge from strong currents, enabling other marine species to hide, grow and live there. Pallets introduce another important growth medium for various marine organisms – wood. The structure is full of cavities (packed oyster shells) where small organisms or juvenile fish can hide.
8. Minimal care to fall to the right position	3	While there is no need for divers to take care that the structures fall correctly, some amount of preparatory work on the deck is required to ensure units will fall to the right position: steering the vessel deploy units in the right position to the currents, arranging them correctly into the rows and connecting them to the leading rope.
9. Lightweight	4	Each gabion weighs around 35kg, which is a safe weight to be lifted and carried by 2 people. Once assembled, the whole unit weighs around 80kg, but it will not be lifted and will be deployed using an anchor and a pull force.
10. Integration into the hatchery	5	Gabions can be placed into the hatchery with empty oyster shells inside to facilitate direct spat fall on them. Later on, gabions are transported to the ship and assembled into the unit on the deck.
11. Possibility to locate	4	This unit row is large, stable and does not get washed away. By geo-tagging the deployment location, it is possible to allocate these structures when needed. Structures are large and connected in with a leading rope, so they can easily be detected with a sonar to find their exact position.
12. Minimal need to retrieve	5	Oyster units are made of biodegradable and naturally occurring materials (in the North Sea). Therefore, there is no legal obligation to retrieve them as they degrade and integrate into the marine environment.

Requirements (non-negotiable, to be achieved):

- **Structures should be structurally independent of the windmills.** The deployed unit rows are independent of the windmills and stabilize themselves due to the weight of the whole row.
- **Structures should not be toxic to the marine environment.** All parts are made of non-toxic materials: wooden pallets are heat-treated without applying any fumigation methods. Other parts are made of bare steel, which corrodes without releasing toxic particles. Cotton or jute fibre lashings biodegrade without releasing toxic elements as well.

Analysis of the final design has shown that the solution is feasible in terms of effective oyster protection and scalability. Further evaluation was done, which included the final design comparison with the current solutions, the final design's limitations, and future research, see Chapter 6.

CHAPTER 6: CONCLUSIONS

6.1 Comparison with the current solutions
6.2 Limitations
6.3 Recommendations & future research
6.4 Personal reflection

Learning by doing: testing the assembly for one of the concepts

6.1 Comparison with current solutions

In comparison, to previously discussed solutions (for details, see Chapter 2) final design is a more scalable solution for larger marine restoration areas and focuses on finding a balance between the criteria instead of being only effective at certain points (Figure 102).

A scalable solution

The price of the final design is comparative to the approach where loose spat on shell is just thrown into the area (Figure 102, A), additional structure (steel mesh and pallets) comprises only 8% of the whole unit price due to highly standardized and widely available parts. But differently from solution A, the final design adds more protection to improve oyster survivability and less spat on shell might be needed to regenerate self-sufficient oyster reefs. Considering a high Flat Oyster spat on shell price and limited availability, the final design with improved young oyster protection is likely to be cheaper to implement than any other aforementioned solution.

A fast deployment where all units slide off from the deck at once without heavy-duty equipment will allow faster deployment than most solutions (Figure 102, B, C, D, E, F). Considering high staff and rental costs for offshore deployment operations, fast deployment further reduces the costs for the oyster reef regeneration.

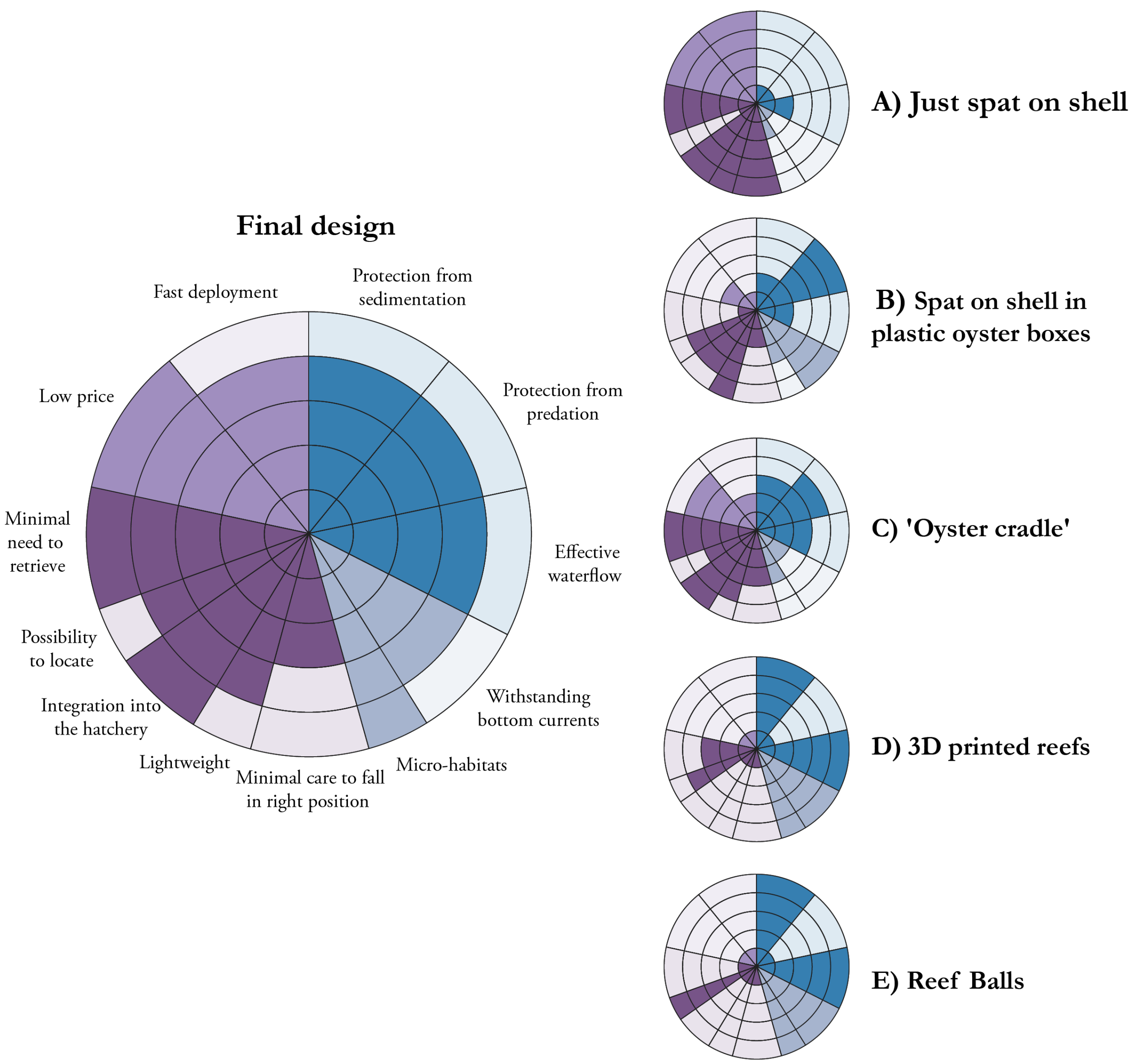


Figure 102: Final design compared to current solutions discussed in Chapter 2.

Balance in criteria

Regarding oyster survival criteria, many solutions on the market may perform very well but one weak point can have a detrimental effect even if other oyster survival criteria are satisfied. For example, some designs offer good and effective waterflow but do not provide additional barriers for the predators (Figure 102, D, E). Differently, other solutions may protect oysters from predation very effectively but run the high risk of limiting the waterflow essential for oyster survival (Figure 102, B). In comparison, the final design performs in balance with all oyster survival criteria to avoid these severe weak points.

The majority of the solutions (Figure 102, A, B, C) aim directly at one task – regenerating the oyster population, and apart from introducing oysters, they do not provide many additional micro-habitats for other marine species. Differently, designs providing these micro-habitats (solution D, E) are expensive to manufacture due to large amounts of material and expensive manufacturing. In comparison, the final design is primarily aimed at successfully introducing young oysters, but at the same time provides a variety of micro-habitats (varied materials as growth mediums and places with varied waterflow) for other marine species, all while keeping the price affordable to scale in large areas.

6.2 Limitations

The project and the final design have some limitations, which are discussed below:

1. Structural integrity tests were done with a real-scale prototype, but the impacts of the waterflow on structural stability and sedimentation patterns were tested only theoretically. In each deployment area, sedimentation and waterflow dynamics might be different; therefore, it was not possible to predict a more accurate oyster survivability outcome just by doing theoretical calculations.

2. The deployment procedure and fall position were not tested with these units. Some uncertainty about deployment operation and unit fall position persists and should be addressed in the field tests.

Figure 103: Additional board can act as a support to guide and maintain the units in the right position.

There is a chance that there will be not enough tension on the lead rope and units may fall on the front or the backside. In that case, they can be supported with an additional board to guide the unit position and prevent it from falling to either side (Figure 103).

3. The most suitable mesh for this design is non-galvanized, 2mm wire with 40x40mm gaps, which is not a standard size and could have limited availability or only be done when ordered directly from the mesh suppliers. 3mm mesh with 40x40mm gaps is more widely available and could be used, but more than 2 years might be needed until this thicker wire degrades, which could compromise oyster survival due to limited space inside the gabion. Oysters positioned on the outside layers will be able to outgrow the structure, but the ones in the middle might have a lower chance of survival.

4. Deployment operation still includes a big part of manual labour for unit assembly and connecting them into one continuous string. Due to a limited spat on shell supply, deployment is not expected to reach a large enough scale to invest in highly automated processes within several years, leaving operations with some manual labour as the preferred solution. The final design can be considered as a step towards scaled-up deployment, but it would not be effective to deploy oysters in 1 km^2 due to time and financial limitations.

6.3 Recommendations & future research

As described in the 6.2 Limitations chapter, there are multiple uncertainties about how this design will function in an offshore environment. Field tests should be done to determine how the unit design impacts the ecological criteria for oyster survivability and broader ecological success: what is the oyster survivability after 1, 2 and 3 consecutive years, what are the sedimentation patterns and how stable are the units against the water currents. In addition, during deployment operation, the unit fall position should be observed to see if additional support boards are needed.

Determining oyster survival rate in 3 years can provide better-quality data which could be used to better determine the costs for other oyster reef restoration sites because current calculations are based on high uncertainty assumptions.

Restoring the North Sea ecosystem by bringing back the flat oysters is one of many possible interventions. It could be explored how deploying multiple species can reinforce the positive effects for ecosystem restoration. In that case, the design could be adapted to cater to multi-species deployment and placement.

6.4 Personal reflection

Research by design and iterative approach

In this project, multiple design methods were used with an overarching methodology of research by design. Research by design approach led to exploration, development, and testing of different ideas in multiple micro-iterations. While exploring these ideas, the overarching macro-iterations gave a clear structure and understanding of what needs to be achieved in each phase, which helped when dealing with the unknown design outcomes. Starting from the fuzzy beginning, each iteration aimed at a more specific design outcome (deciding on design direction, or concept choice) to lead to the final solution. Making low-fidelity prototypes early on has helped to filter out the ideas and decide on the most optimal solutions. In addition, building and getting feedback on the prototypes has helped to collect the required knowledge along the way.

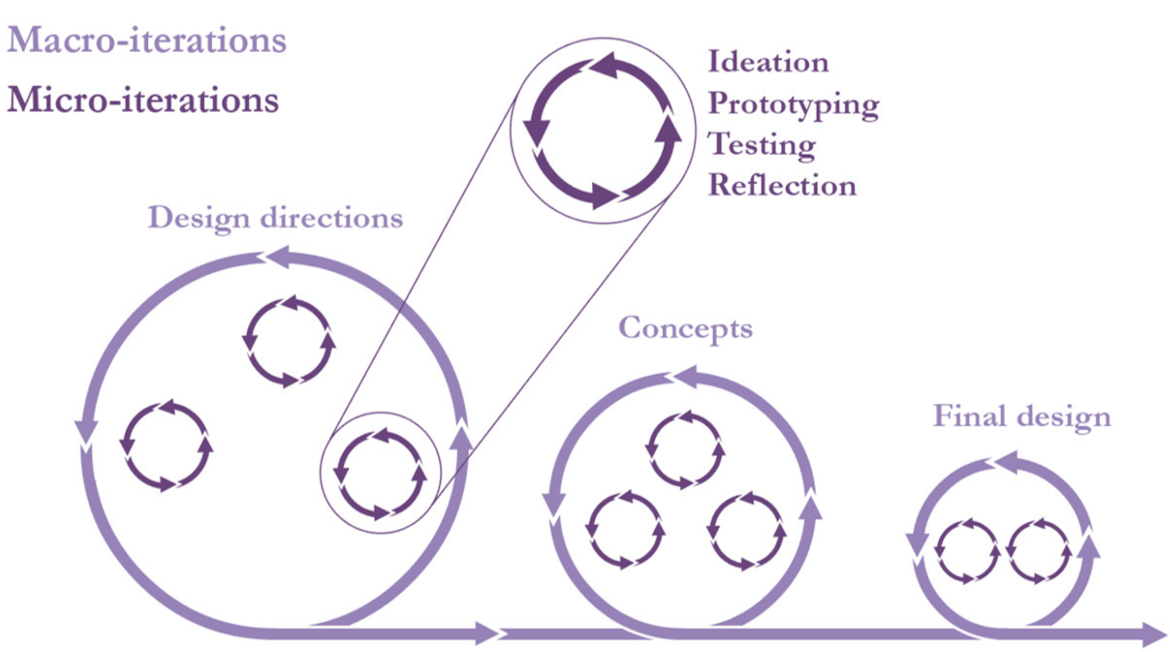


Figure 104: Iterative approach in this project has led to extensive idea exploration while maintaining

Design methods: Whole Systems Mapping & Biomimicry

As a pair of methods, Whole Systems Mapping (WSM) and Biomimicry have worked together well during the exploration for nature-centric solutions, especially at the beginning of the project. In later stages, WSM was mainly used without Biomimicry.

WSM helped to create a good overview of the current system and to think about how each design intervention may affect various system components. For example, when brainstorming on the system map and thinking about different ways to deploy oysters, it was a constant reminder to think about how the ideas will be integrated into the hatchery. WSM was also useful in formulating primary questions which were used for further context research or search for design inspiration using Biomimicry. A part of the WSM, the Decision Matrix, has helped to reflect back on the design criteria and evaluate different ideas accordingly. Some decision matrix limitations were acknowledged: when ideas are in the early stage of development, many assumptions are made to deal with the unknown outcomes, which if not dealt with properly, will result in superficial evaluation and scores which can be easily manipulated. Therefore, the evaluated ideas were tested by making small-scale prototypes and only then Decision Matrix was used as a guiding tool together with argumentation to make a sound evaluation.

During the brainstorming phase in WSM, it is stated that brainstorming should take place evenly throughout the system map. During the first iteration of this project, brainstorming has indeed been done throughout the system map to explore the possible solution space. Differently, in the second iteration, there was more focus on scalability, and the majority of brainstorming ideas were focused on deployment and different unit configurations. Therefore, depending on the iteration and design challenge, brainstorming on the system map could be approached in two possible ways: brainstorming throughout the whole system to get more radical solutions; brainstorming with a focus on critical aspects of the system, and thinking about how these ideas can be integrated into other system parts.

Biomimicry was effective in the beginning, to get the initial inspiration because various biology strategies from marine organisms could be applied back to the design for the marine ecosystem. But in the later stages of the project, when scalability was highlighted as a focus challenge, biomimicry did not provide much insight for further design improvements, because those ideas would require complex manufacturing techniques or novel materials which would bring up the costs. This is why even if the primary inspiration was biomimicry, further iterations did not include a Biomimicry method step.

Thinking with hands

Making low-fidelity clay figures and small-scale prototypes has helped in communicating the ideas to the experts and collecting their feedback. Discussions with small-scale models were richer in feedback, and people would express that they were feeling more energized by seeing physical models. In addition, letting myself or other people play, touch, and interact with small-scale prototypes, making hands busy, would spark a different way of thought – 'thinking with hands'. This allowed more nuanced insights about the construction, possible deployment scenarios or the way it would work on the seafloor. This approach has led to some extremely important ideas in the project and impacted multiple design decisions: for example, positioning gabions in a diamond shape to reduce oyster mortality or connecting 2 gabions in a double diamond shape have been the outcomes of interactions with the interim prototypes. Therefore, prototypes not only can be used for communicating ideas more clearly but also as a way to ideate further for additional improvements.

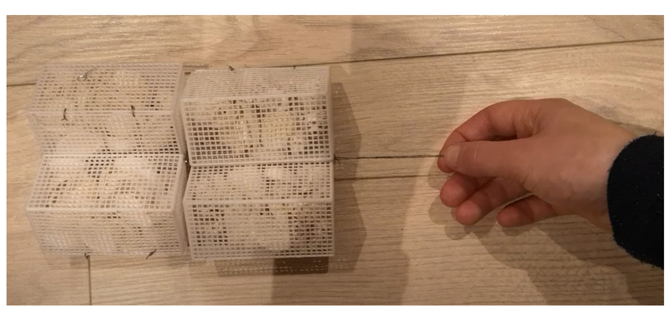


Figure 105: Testing out the leading rope attachments with two concept models.

Design for biodiversity

When designing for biodiversity, findings from research in ecology inform design on which interventions can be the most effective in a specific ecosystem. Also, the end users in this project, such as various benthic organisms, cannot be interviewed directly to understand their preferences. Therefore, ecology and biology experts become the mediators between the design and its end users, by providing insights about the North Sea ecosystem, and offshore work context and giving feedback on the different designs. In later product development stages, the marine ecosystem could be 'interviewed' by testing how it responds to the design, but these testing times are dependent on the season and may take a long time before clear outcomes can be seen. Therefore, working in a multidisciplinary team with ecology and biology experts is one of the key aspects of designing solutions for ecosystem regeneration.

As often happens in multidisciplinary teams, every specific field and profession has its own vocabulary. Many new ecological concepts and words had to be learned, but organized field trips where reef restoration context could be experienced and having low-fidelity prototypes during the interviews with experts have helped in understanding each other more easily.

Finally, designing for nature teaches to deal with uncertainty, because it is not possible to translate the whole ecosystem into a collection of parameters and be sure that the design will work exactly how it is supposed to. For example, it is impossible to state how much reef can be regenerated during the restoration project, because of the numerous unknown factors that neither designers nor ecology or biology experts may be aware of. And once the design is deployed, it can take multiple years of monitoring until some implications to the local ecosystem can be determined. This, however, can be hard to explain to other stakeholders who are used to accurate predictions and clear results. Therefore, it is important to keep this uncertainty in mind and communicate it clearly to other stakeholders, to ensure stakeholder agreement and allow the best possibilities for learning.

Figure 106: Deploying young oysters in Voordelta with ARK Rewilding Nederland, Waardenburg Ecology and Stichting Zeeschelp. Photo credits: Gwenaël Hanon, ARK Rewilding Nederland.

REFERENCES

Álvarez, H., Perry, A. L., Blanco, J., García, S., & Aguilar, R. (2019). Protecting The North Sea: New Research for Biodiversity Recovery. In *https://europe.oceana.org/*. Oceana, Madrid. Retrieved November 7, 2022, from https://europe.oceana.org/wp-content/uploads/sites/26/d_files/north_sea_overview_report_web.pdf

BESE products. (2021, November 18). *A paste made from shell hash enhances oyster recruitment*. BESE Products. https://www.bese-products.com/biodegradable-products/reef-paste/

BESE products. (2022, January 13). *Biodegradable mesh bags from cellulose or biopolymers*. BESE Products. https://www.bese-products.com/biodegradable-products/bese-mesh-bags/

Bos, O. G., Gittenberger, A., Boois, I. J. D., Asch, M. V., Wal, J. T. V. D., Cremer, J., Hoorn, B. V. D., Pieterse, S., & Bakker, P. A. J. (2016). Soortenlijst Nederlandse Noordzee. In *https://edepot.wur.nl/* (Research Report C125/16A). Wageningen Marine Research. https://edepot.wur.nl/401117

Bruce, D. G., Cornwell, J. C., Harris, L., Ihde, T. F., Kellogg, M. L., Knoche, S., Lipcius, R. N., McCulloch-Prosser, D. N., McIninch, S. P., Ogburn, M. B., Seitz, R. D., Testa, J., Westby, S. R., & Vogt, B. (2021). A Synopsis of Research on the Ecosystem Services Provided by Large-Scale Oyster Restoration in the Chesapeake Bay. In *NOAA Tech. Memo.* (NMFS-OHC-8). NOAA Chesapeake Bay Office. https://spo.nmfs.noaa.gov/sites/default/files/TMOHC8.pdf

Christianen, M. J. A., Lengkeek, W., Bergsma, J. H., Coolen, J. W. P., Didderen, K., Dorenbosch, M., Driessen, F. M. F., Kamermans, P., Reuchlin-Hugenholtz, E., Sas, H., Smaal, A., Van Den Wijngaard, K. A., & Van Der Have, T. M. (2018). Return of the native facilitated by the invasive? Population composition, substrate preferences and epibenthic species richness of a recently discovered shellfish reef with native European flat oysters (*Ostrea edulis*) in the North Sea. *Marine Biology Research*, *14*(6), 590–597. https://doi.org/10.1080/17451000.2018.1498520

Colsoul, B., Pouvreau, S., Di Poi, C., Pouil, S., Merk, V., Peter, C., Boersma, M., & Pogoda, B. (2020). Addressing critical limitations of oyster (*Ostrea edulis*) restoration: Identification of nature-based substrates for hatchery production and recruitment in the field. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(11), 2101–2115. https://doi.org/10.1002/aqc.3454

DHI. (2020). Metocean Study: Hollandse Kust (west) Wind Farm Zone: Version December 2020. In *https://offshorewind.rvo.nl/* (CR-SC-DNVGL-SE-0190-05500-0 Metocean Conditions (west) Rev.0). https://offshorewind.rvo.nl/file/download/378260ad-a965-4dec-8182-70b61bc5e118/hkw_20220725_dhi_metocean-desk-study-report-f.pdf

Didderen, K., Have, T. V. D., Bergsma, J. H., Jagt, H. V. D., Kamermans, P., Sas, H., & Lengkeek, W. (2019). *Shellfish bed restoration pilots Voordelta, Netherlands Annual report 2018*. https://www.researchgate.net/publication/351706889_Shellfish_bed_restoration_pilots_Voordelta_Netherlands_Annual_report_2018

Didderen, K., Lengkeek, W., Bergsma, J. H., Dongen, U. V., Driessen, F. M. F., & Kamermans, P. (2020). WWF & ARK Borkum Reef Ground oyster pilot: Active restoration of native oysters in the North Sea - monitoring September 2019. In *https://www.wwf.nl/* (Bureau Waardenburg Report no.19-227). Bureau Waardenburg, Culemborg. https://www.wwf.nl/globalassets/pdf/wwf-and-ark-borkum-reef-ground-oyster-pilot.pdf

Dilkes-Hoffman, L. S., Lant, P. A., Laycock, B., & Pratt, S. (2019). The rate of biodegradation of PHA bioplastics in the marine environment: A meta-study. *Marine Pollution Bulletin*, *142*, 15–24. https://doi.org/10.1016/j.marpolbul.2019.03.020

DTU, & Aage, N. (2020). *Interactive 2D TopOpt App*. https://www.topopt.mek.dtu.dk. https://www.topopt.mek.dtu.dk/apps-and-software/interactive-2d-topopt-app

Duren, L. A. V., Gittenberger, A., Smaal, A. C., Koningsveld, M. V., Osinga, R., Lelij, J. A. C. V. D., & Vries, M. B. D. (2017). Rich Reefs in the North Sea: Exploring the possibilities of promoting the establishment of natural reefs and colonisation of artificial hard substrate. In *https://publications.deltares.nl/* (No. 1221293–000). Deltares. https://publications.deltares.nl/1221293_000_Eng.pdf

EcoShape. (2020, October 6). *Oyster reefs - EcoShape*. EcoShape - EN. https://www.ecoshape.org/en/pilots/oyster-reefs/

EnZar. (n.d.). *How Does Welded Gabion Basket Work In Oyster Reef Restoration?* https://www.gabionbarriers.com/technology/gabion-basket-oyster-shell.html

FAO. (2022). *Ostrea edulis. Cultured Aquatic Species Information Programme. Text by Goulletquer, P.. Fisheries and Aquaculture Division.* https://www.fao.org/. Retrieved November 7, 2022, from https://www.fao.org/fishery/en/culturedspecies/ostrea_edulis/en

FEFPEB. (2012). *ISPM 15*. https://www.fefpeb.eu/wooden-packaging/ispm-15

Fowler, A. M., Jørgensen, A. M., Coolen, J. W. P., Jones, D. O. B., Svendsen, J. C., Brabant, R., Rumes, B., & Degraer, S. (2019). The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. *ICES Journal of Marine Science*, *77*(3), 1109–1126. https://doi.org/10.1093/icesjms/fsz143

Freiwald, A., Fosså, J.H., Grehan, A., Koslow, T., Roberts, J.M. 2004. Cold-water Coral Reefs. UNEP-WCMC, Cambridge, UK.

Gușatu, L. F., Menegon, S., Depellegrin, D., Zuidema, C., Faaij, A., & Yamu, C. (2021). Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-89537-1

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P., Perry, M. T., Selig, E. R., Spalding, M., Steneck, R., & Watson, R. (2008). A Global Map of Human Impact on Marine Ecosystems. *Science*, *319*(5865), 948–952. https://doi.org/10.1126/science.1149345

Hanna, S. K., Miller, R. J., Muller, E. B., Nisbet, R. M., & Lenihan, H. S. (2013). Impact of Engineered Zinc Oxide Nanoparticles on the Individual Performance of Mytilus galloprovincialis. *PLoS ONE*, *8*(4), e61800. https://doi.org/10.1371/journal.pone.0061800

Hofstede, R. T., Driessen, F., Elzinga, P., Van Koningsveld, M., & Schutter, M. (2022). Offshore wind farms contribute to epibenthic biodiversity in the North Sea. *Journal* *of Sea Research*, *185*, 102229. https://doi.org/10.1016/j.seares.2022.102229

Kamermans, P., Walles, B., Kraan, M., Van Duren, L., Kleissen, F., Van Der Have, T., Smaal, A., & Poelman, M. (2018). Offshore Wind Farms as Potential Locations for Flat Oyster (Ostrea edulis) Restoration in the Dutch North Sea. *Sustainability*, *10*(11), 3942. https://doi.org/10.3390/su10113942

Khodabux, W., Causon, P., & Brennan, F. (2020). Profiling Corrosion Rates for Offshore Wind Turbines with Depth in the North Sea. *Energies*, *13*(10), 2518. https://doi.org/10.3390/en13102518

Lee, L. A. (2022, July 7). *Sunday Story: The Mighty Bivalve*. richmondmagazine.com. https://richmondmagazine.com/news/sunday-story/the-mighty-bivalve/

Lengkeek, W., Coolen, J., Gittenberger, A., & Schrieken, N. (2013). ecological relevance of shipwrecks in the north sea. *Nederlandse Faunistische Mededelingen*, *41*, ISSN 0169-2453, 448834. https://library.wur.nl/WebQuery/wurpubs/448834

Maneiro, V., Santos, Y., Pazos, A. J., Silva, A., Torres-Corral, Y., Sánchez, J. L., & Pérez-Parallé, M. L. (2020). Effects of food ration, water flow rate and bacteriological levels of broodstock on the reproductive conditioning of the European flat oyster (Ostrea edulis, Linnaeus 1758). *Aquaculture Reports*, *18*, 100412. https://doi.org/10.1016/j.aqrep.2020.100412

McAfee, D., Williams, B. R., McLeod, L., Reuter, A., Wheaton, Z., & Connell, S. D. (2022). Soundscape enrichment enhances recruitment and habitat building on new oyster reef restorations. *Journal of Applied Ecology*. https://doi.org/10.1111/1365-2664.14307

Netherlands Enterprise Agency (RVO). (2021). Hollandse Kust (west) Wind Farm Zone: Project and Site Description. In *https://offshorewind.rvo.nl/*. https://offshorewind.rvo.nl/file/download/3b960c83-6a0c-4d19-9164-f10cdb77873f/1625051036hkw_20210630_project%20and%20site%20description-f.pdf

NIOZ. (2017, December 12). *Gerepareerde RV Pelagia vertrekt woensdag 13 december op NICO-expeditie - NIOZ*. nioz.nl. https://www.nioz.nl/en/news/gerepareerde-rv-pelagia-vertrekt-woensdag-13-december-op-nico-expeditie

Nitsch, C. K., Walters, L. J., Sacks, J. S., Sacks, P. E., & Chambers, L. G. (2021). Biodegradable Material for Oyster Reef Restoration: First-Year Performance and Biogeochemical Considerations in a Coastal Lagoon. *Sustainability*, *13*(13), 7415. https://doi.org/10.3390/su13137415

NOAA. (2021, February). *Significant Progress for Chesapeake Bay Oyster Reef Restoration—Yes, Even in 2020*. https://www.fisheries.noaa.gov/feature-story/significant-progress-chesapeake-bay-oyster-reef-restoration-yes-even-2020

Olsen OT. 1883. The Piscatorial Atlas of the North Sea, English and St. George’s Channels: Illustrating the Fishing Ports, Boats, Gear, Species of Fish (How, Where, and when Caught), and Other Information Concerning Fish and Fisheries. Olsen. 50 pages.

Open Seas. (2021). *Bottom dragging*. openseas.org.uk. https://www.openseas.org.uk/evidence/

Ørsted. (2022, May). *Ørsted en TotalEnergies doen samen mee aan aanbesteding offshore windpark Hollandse Kust West*. https://orsted.nl/. Retrieved November 7, 2022, from https://orsted.nl/news-archive/2022/05/orsted-en-totalenergies-doen-samen-mee-aan-aanbesteding-offshore-windpark-hollandse-kust-west

Paulsen, B. T., Roetert, T., Raaijmakers, T., Forzoni, A., Hoekstra, R., & Steijn, P. V. (2016). Morphodynamics of Hollandse Kust (zuid) Wind Farm Zone. In *Deltares* (No. 1230851–000). Deltares. https://offshorewind.rvo.nl/file/download/bd489750-e879-4da5-beb3-51ac88ead3f6/1483456263hkz_20161222_deltares_morphologystudy_del_v03_f_compleet.pdf

Pogoda, B., Brown, J., Hancock, B., Preston, J., Pouvreau, S., Kamermans, P., Sanderson, W., & Von Nordheim, H. (2019). The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquatic Living Resources*, *32*, 13. https://doi.org/10.1051/alr/2019012

Rämä, T., Nordén, J., Davey, M. L., Mathiassen, G. H., Spatafora, J. W., & Kauserud, H. (2014). Fungi ahoy! Diversity on marine wooden substrata in the high North. *Fungal Ecology*, *8*, 46–58. https://doi.org/10.1016/j.funeco.2013.12.002

Rijksoverheid. (2022, March 18). *Kabinet verdubbelt productie windenergie op zee* [Press release]. https://www.rijksoverheid.nl/actueel/nieuws/2022/03/18/kabinet-verdubbelt-productie-windenergie-op-zee

Robert, R., Borel, M., Pichot, Y., & Trut, G. (1991). Growth and mortality of the European oyster Ostrea edulis in the Bay of Arcachon (France). *Aquatic Living Resources*, *4*, 265–274. https://archimer.ifremer.fr/doc/00015/12600/9477.pdf

Rodriguez-Perez, A., James, M., Donnan, D. W., Henry, T. B., Møller, L. F., & Sanderson, W. G. (2019). Conservation and restoration of a keystone species: Understanding the settlement preferences of the European oyster (Ostrea edulis). *Marine Pollution Bulletin*, *138*, 312–321. https://doi.org/10.1016/j.marpolbul.2018.11.032

Rotom Europe. (2023). *Display pallet 800x600x120 mm*. Logistiekonline.nl. https://www.logistiekonline.nl/houten-display-pallet-15300ht.html?source=googlebase

Sarker, I., Moore, L. R., & Tetu, S. G. (2021). Investigating zinc toxicity responses in marine Prochlorococcus and Synechococcus. *Microbiology*, *167*(6). https://doi.org/10.1099/mic.0.001064

Sas, H. (2019). *Ostrea Edulis life cycle*. The Rich North Sea. https://www.derijkenoordzee.nl/en/news/life-cycle-of-european-flat-oysters

Sea Ranger Service. (2022, April 16). *Sea Rangers monitor North Sea heritage*. https://searangers.org/2022/04/16/sea-ranger-monitor-north-sea-heritage/

Sela, S., Schroeder, T., Mamoru, M., & Ormsby, M. (2017). Explanatory document for ISPM 15 (Regulation of wood packaging material in international trade). In *ippc.int*. FAO. https://www.ippc.int/static/media/files/publication/en/2017/02/ISPM_15_ED_En_2017-02-10.pdf

Smaal, A. C., Kamermans, P., Have, T. M. V. D., Engelsma, M., & Sas, H. J. W. (2015). Feasibility of Flat Oyster (Ostrea edulis L.) restoration in the Dutch part of the North Sea. In *https://library.wur.nl/* (Report C028/15). IMARES Wageningen UR. https://library.wur.nl/WebQuery/wurpubs/reports/485820

Smit, P. H. (2019, July 10). Natuurherstel bij windpark in Noordzee mislukt: 85 procent geplaatste oesters dood. *De Volkskrant*. Retrieved November 7, 2022, from https://www.volkskrant.nl/nieuws-achtergrond/natuurherstel-bij-windpark-in-noordzee-mislukt-85-procent-geplaatste-oesters-dood~b3c53e9b/?referrer=https%3A%2F%2Fwww.google.com%2F

Sommer, B., Fowler, A. M., Macreadie, P. I., Palandro, D. A., Aziz, A. C., & Booth, D. J. (2019). Decommissioning of offshore oil and gas structures – Environmental opportunities and challenges. *Science of the Total Environment*, *658*, 973–981. https://doi.org/10.1016/j.scitotenv.2018.12.193

Stiles, M. L., Stockbridge, J., Lande, M., & Hirshfield, M. F. (2010). Impacts of Bottom Trawling on Fisheries, Tourism, and the Marine Environment. In *https://oceana.org/*. Oceana. https://oceana.org/wp-content/uploads/sites/18/Trawling_BZ_10may10_toAudrey.pdf

The Natural History Museum. (n.d.). *The sand dollar's skeleton with 6 holes called lunules*. https://www.nhm.ac.uk/our-science/data/echinoid-directory/morphology/dollars/lunules.html

Viñas, V. M., Santos, Y., Pazos, A. J., Silva, A., Torres-Corral, Y., Sánchez, J. L., & Pérez-Parallé, M. L. (2020). Effects of food ration, water flow rate and bacteriological levels of broodstock on the reproductive conditioning of the European flat oyster (Ostrea edulis, Linnaeus 1758). *Aquaculture Reports*, *18*, 100412. https://doi.org/10.1016/j.aqrep.2020.100412

Walters, L. J., Roddenberry, A., Crandall, C., Wayles, J., Donnelly, M., Barry, S. C., Clark, M. W., Escandell, O., Hansen, J. C., Laakkonen, K., & Sacks, P. E. (2022). The Use of Non-Plastic Materials for Oyster Reef and Shoreline Restoration: Understanding What Is Needed and Where the Field Is Headed. *Sustainability*, *14*(13), 8055. https://doi.org/10.3390/su14138055

Wijsman, J. W. M., & Smaal, A. C. (2017). The use of shellfish for pre-filtration of marine intake water in a reverse electro dialysis energy plant. In *https://redstack.nl/* (C078/17). Wageningen Marine Research. https://redstack.nl/wp-content/uploads/2021/02/OOBE-C078_17-Rapport-The-use-of-shellfish-FINAL-J_-Wijsman-mw.pdf

Wilker, J. (2010). *Natural Pacific oyster reef*. Purdue University. https://www.purdue.edu/newsroom/research/2010/100920WilkerOysters.html

Yoon, G. L., Kim, B. T., Kim, B. O., & Han, S. H. (2003). Chemical–mechanical characteristics of crushed oyster-shell. *Waste Management*, *23*(9), 825–834. https://doi.org/10.1016/s0956-053x(02)00159-9

Yung, M. M. N., Mouneyrac, C., & Leung, K. M. Y. (2014). Ecotoxicity of Zinc Oxide Nanoparticles in the Marine Environment. *Encyclopedia of Nanotechnology*, 1–17. https://doi.org/10.1007/978-94-007-6178-0_100970-1

APPENDIX A: DESIGN DIRECTION - DETAILED PROGRESS

Numerous design cycles have taken place throughout the analysis described further, resulting in sketches and low-fidelity prototypes which were used to discuss the directions with design and marine ecology experts. By the end of this design phase, one design direction is chosen for further development.

3.1 Initial cycle – graduation in a day

A full workday was dedicated to going through the project using Whole System Mapping and Biomimicry methods to come up with several prototypes in different design directions. The Whole System Mapping method was used to visualize the process from empty shells being collected from the restaurants to the structures being deployed to offshore environments and interacting with a marine ecosystem, then brainstorming new ideas for it (Figure 1). While brainstorming, several questions arose about how manufacturing, deployment, and functioning possibilities.

A few of those questions ("How to stabilize the structure" and "How does nature provide a varied environment"), were chosen for analysis using Biomimicry: challenge to biology method from which several low-fidelity prototypes have been developed and discussed with experts from ARK. Detailed prototype evaluation and main takeaways can be seen in Figure 2. For the second design cycle, the main takeaways include these requirements and suggestions:

- Structures should offer more protection from predation and sedimentation, otherwise young oyster mortality rate will be significant.
- Connecting single modules into a cluster seems to be an effective idea to stabilize the structures, in addition, it would be easier to deploy the whole cluster instead of single individuals. Finally, the cluster can have a lot of surface variability due to modules piling up on each other.
- Mimicking oyster shell surface irregularities was noted as an effective way to offer variety, further inspirations from oyster shells and reefs should be considered, because they are best adapted for biogenic reef formation.

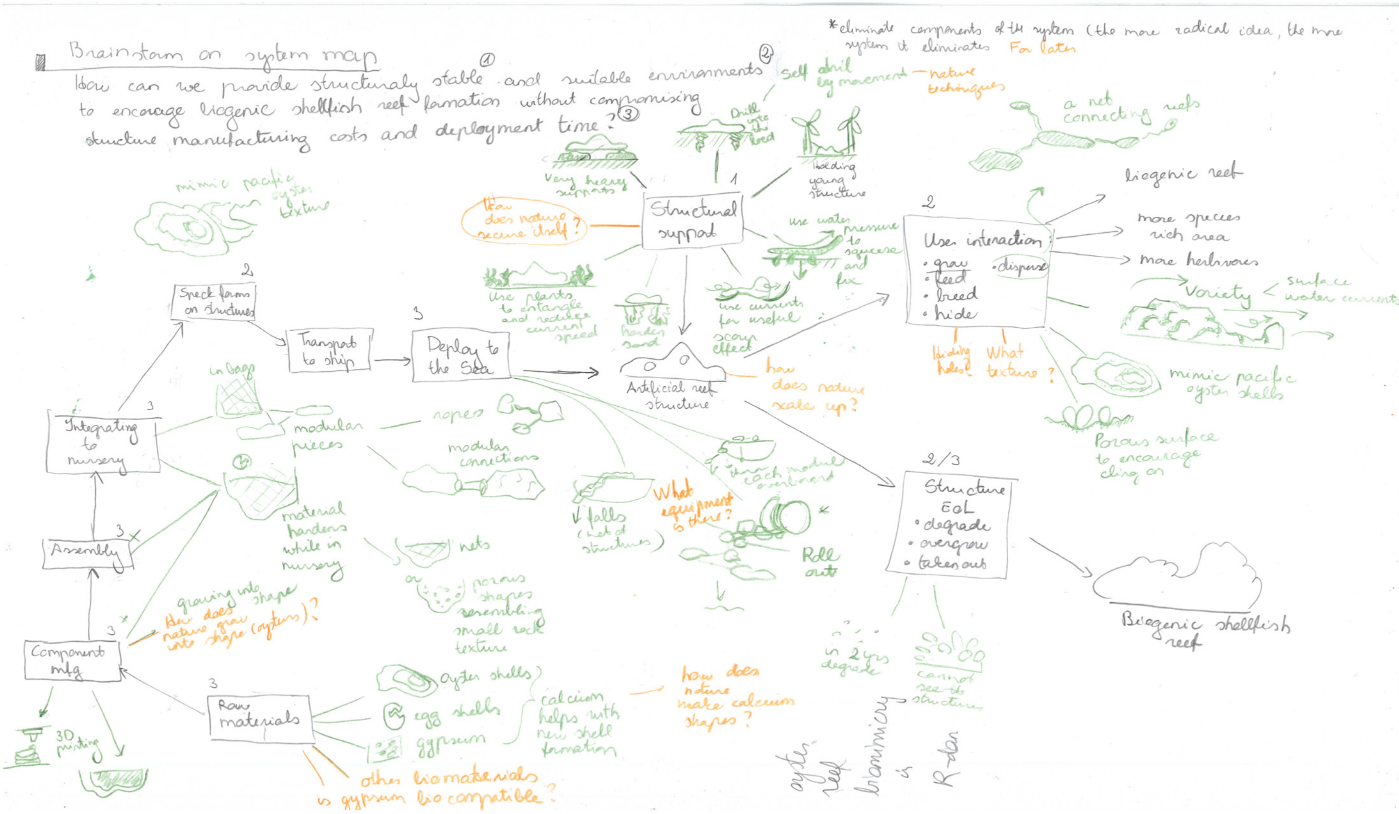


Figure 1: Brainstorm on the system map.

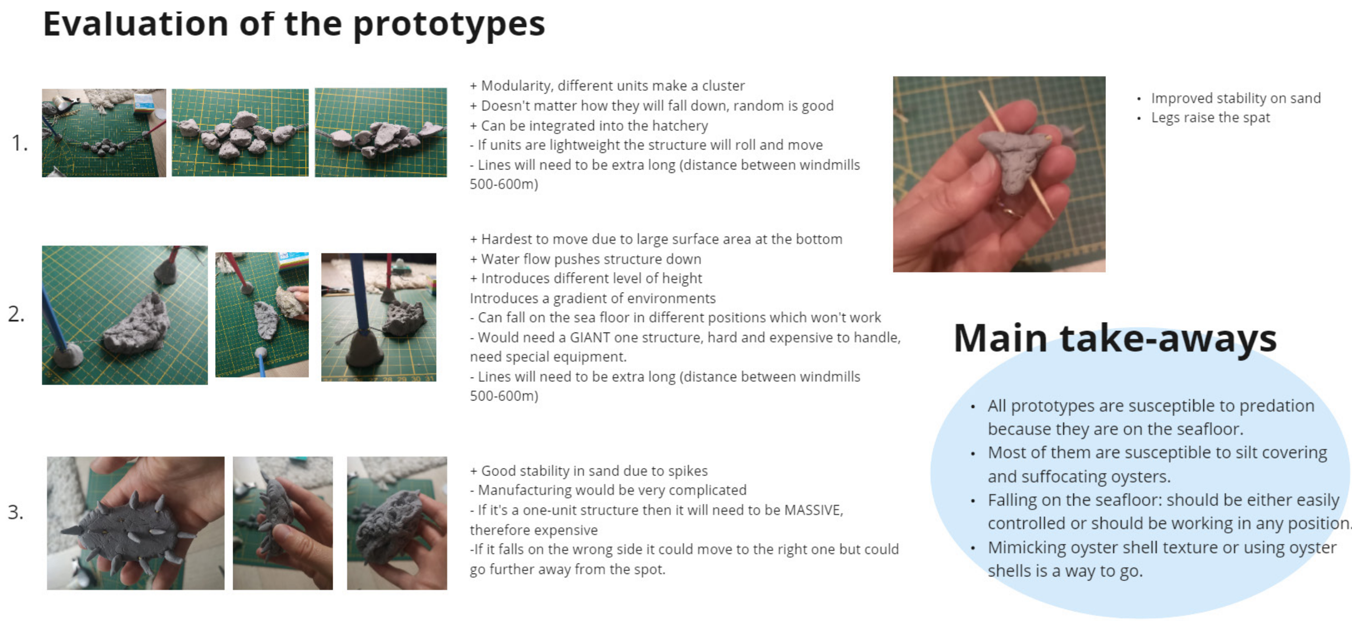


Figure 2: detailed product evaluations and main takeaways.

3.2 Second cycle

After gaining insights from the initial design cycle and additional expert feedback, more design requirements were added regarding viability: Flat oyster survival and broader ecological success. A more detailed context analysis was done to understand the North Sea offshore environment, Biomimicry method was used to gain inspiration for new design ideas.

Context analysis

More detailed context analysis was carried out with literature research and talks with the client, mainly about the flat oyster and its survival and the surrounding ecosystem. The insights are described as the requirements with a summary in Figure 3 and Figure 4.

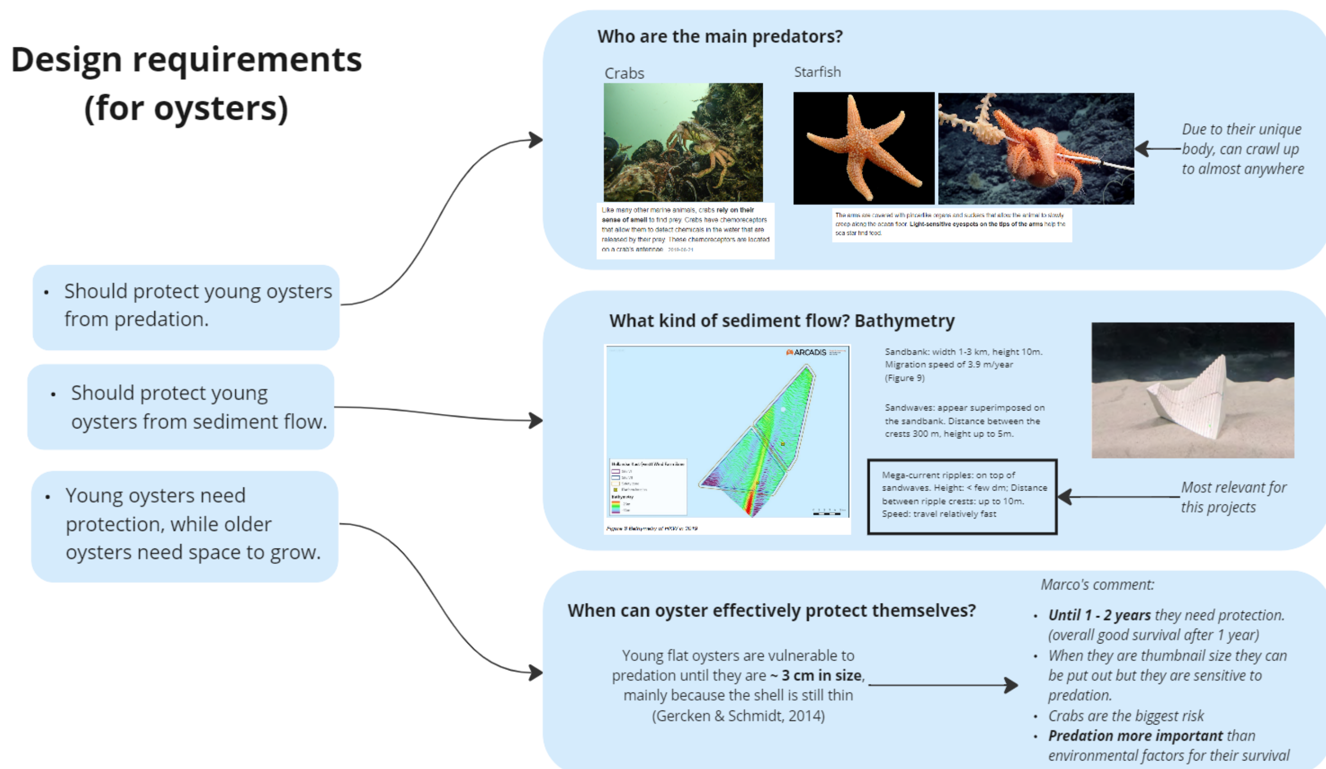


Figure 3: Design requirements for oysters and related context details.

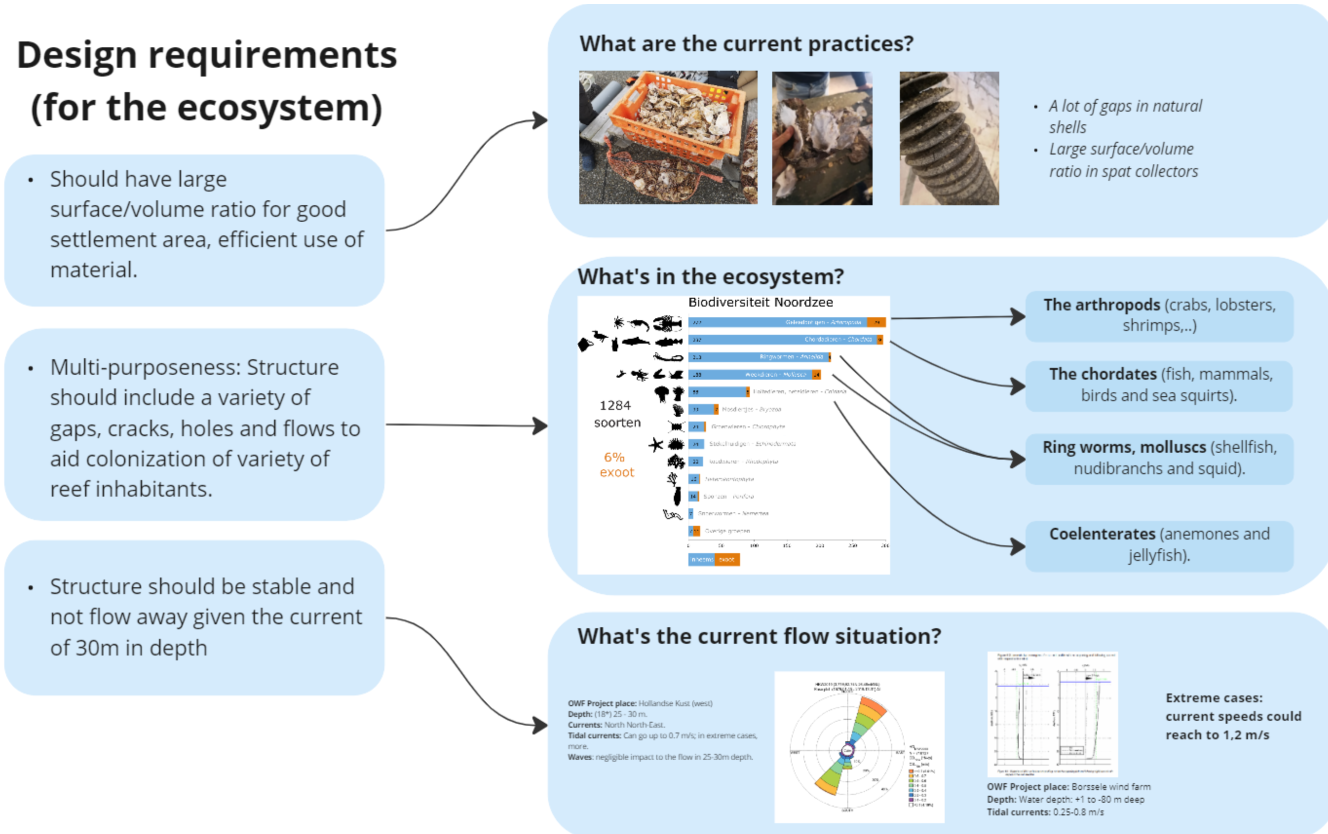


Figure 4: Design requirements for the ecosystem and the related context details.

Biomimicry: challenge to biology

The requirements were transformed into questions for nature; for each question research was carried out using the Asknature.org website. Once a design strategy was found, a search for current design applications for each strategy also led to insights about how the strategy is adapted in the design field already (Figure 5, Figure 6, Figure 7).

Translating biology to design: two main directions

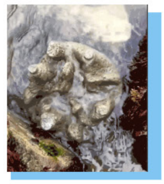
With the insights from Context Analysis and Biomimicry, it was clear that working with empty shells seems to be a promising direction. Firstly, oyster shells and their shape are already highly irregular introducing the needed variety to the structure design. Secondly, using empty oyster shells as a waste source from restaurants reduces the need for virgin materials and returns useful nutrients back into the sea. Therefore, it was chosen to use oyster shells as a medium for the design. There are multiple ways the shells could make these structures, the main design directions were categorized between “Shells bound with a medium” and “Shells bound with external structure”.

Nature strategy

How does nature protect itself from predators?

Oyster shells are rough and irregular. The bulky and complex external structure of an oyster reef shields a complex inner world of crevices, fissures, and gaps that develop from the oysters' nonuniformity. Larvae find protection within these "interstitial folds," where calmer waters exert weaker stresses. Inside these protected zones, tightly packed vertical surfaces provide additional refuge, restricting access for predators such as the blue crab.

How is it applied currently?



Grow oyster reef tile: Uses oyster concrete, can be casted or 3D printed.

Need to ensure that it stands upright

For coral reefs:

Coral carbonate: 3D printed form Calcium carbonate with binder jet printing.

Multi-sided function, including many gaps and holes

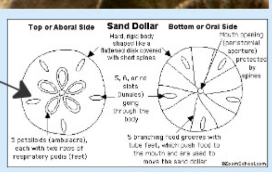
3D printed with Terracota clay, one sided function

Figure 5: Biomimicry strategy for protection.

Nature strategy

How does nature live on sand?

How does nature create stability in water flow?



Lunules

Sand dollar.
The function of lunules: they act as pressure drainage channels and thus help prevent the animal being lifter out of the sediment by wave action. Hydrodynamic tests have shown that sand dollars with lunules can live in settings with higher water flow rates.

How is it applied currently?

Creating holes

...or water channels

Figure 6: Biomimicry strategy for stability.

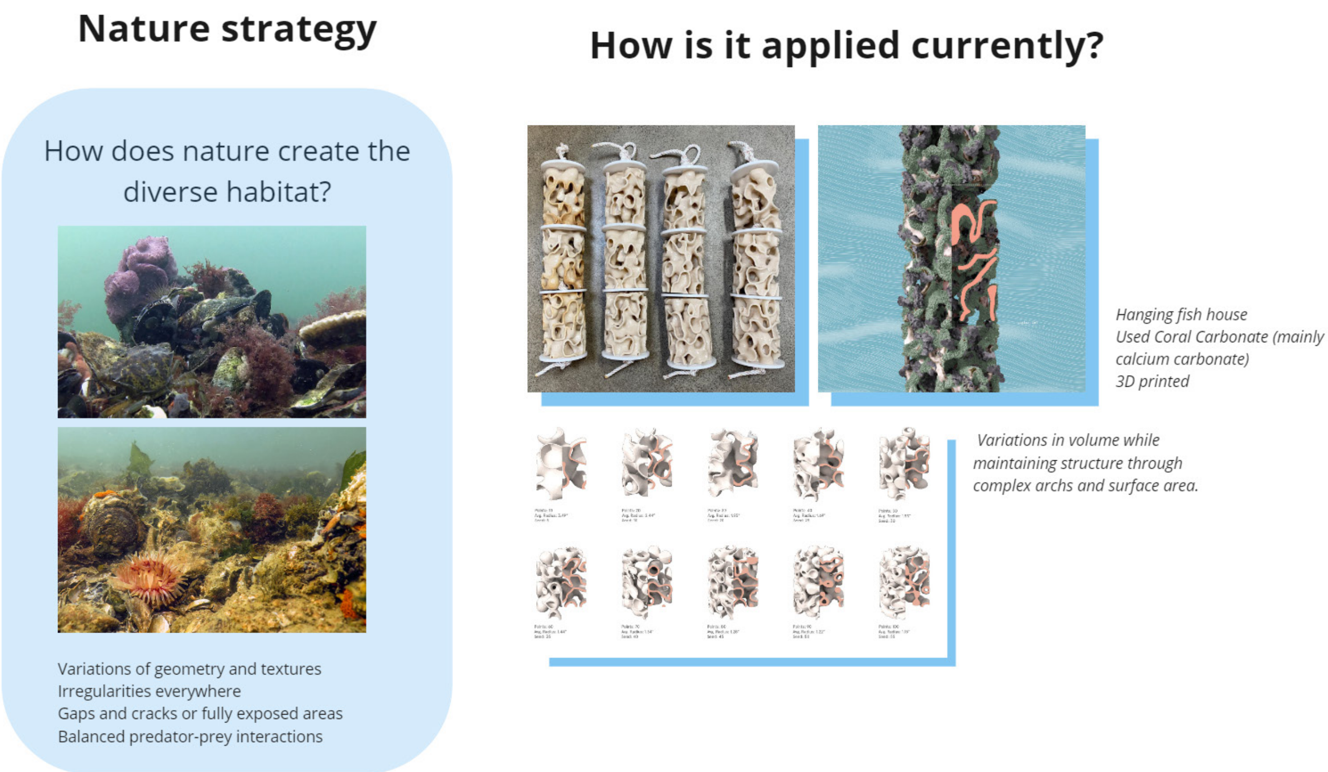


Figure 7: Biomimicry strategy for diversity.

Shells bound with a medium

One of the directions was to mimic the oyster reef structure and find ways to glue oysters back together (Figure 8) into a desired shape. For this, additional material research was done, to see what kind of materials would be similar to oyster glue. In addition, iterations on the shape were done while mimicking the details of the oyster reef (Figure 9).

Figure 8: The goal of this idea would be to stick empty oyster shells in a similar way as in the oyster reef.

Various shapes were evaluated according to how stable will they be once deployed on the seafloor, how easy they are to form, and how large is the surface area-to-volume ratio. Torus shapes, inspired by Actinia (see Figure 10) provided good stability on the surface, because even if they fall on any edge, they will eventually drop on one of the two major sides. Using them as modules to make a cluster could offer even more surface variety if structures fall slightly on each other (Figure 11).

Figure 9: Shape exploration using modelling clay.

Figure 10: Actinia equina with tentacles growing in a circular pattern around the mouth. (Image credit: Attrattorestrano at Italian Wikipedia, 2008)

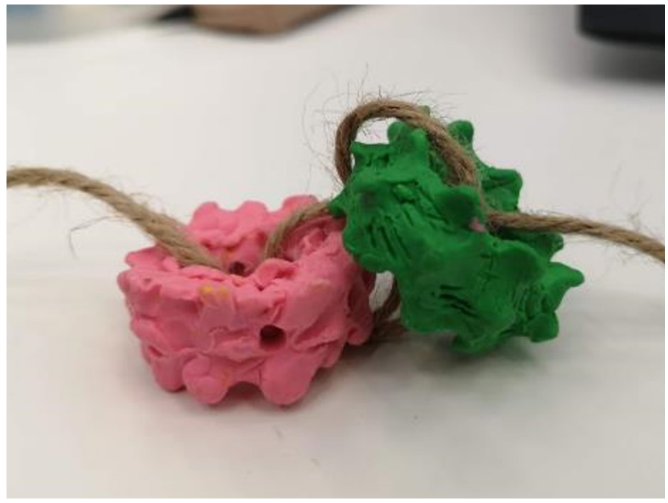


Figure 11: Torus-shaped modules could be tied into a cluster to offer more geometrical variety and stability on the seafloor.

Scale model

A parametric design model was created showcasing how the torus shape with irregular surface from oyster shells could look (Figure 12). High surface area/volume ratio, crenellations and sharp edges provide an effective surface for oyster spat settlement and protection against predation. The nature strategy of the Sand Dollar (Figure 13) was applied by incorporating holes that allow some water to go through the structure. In this case, holes act as pressure-drainage places making the structure more stable against the water currents.

Considering the large-scale deployment, it would be most effective to form large structures with a great number of cavities formed by empty shells for various reasons. Firstly, if structures are to be connected with each other (see Figure 11) to improve deployment efficiency and retrievability, having a lower number of large-scale units will minimize the labour costs of connecting them. Secondly, as juvenile oysters grow, they will need protection for at least 1 year (grow up to around 3mm in size (Robert et al., 1991)), therefore structures should provide large enough cavities. Finally, larger structures can provide higher structural variety and raise the young oysters from the seabed more effectively as opposed to small elements. Each torus structure would be around 70cm in outside diameter.

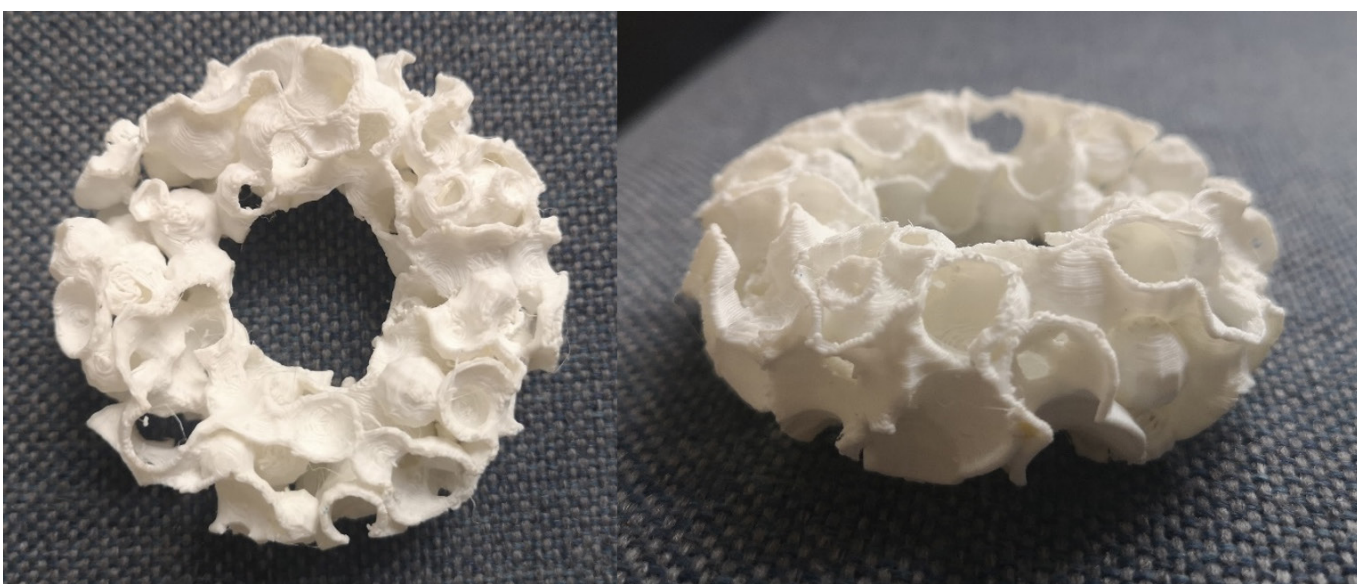


Figure 12: Parametric design model (scale 1/10) combining the chosen shape and mimicking the irregularities of the oyster reef.

Material

What is the most suitable material to bind these empty oyster shells together? It is still unknown, with several possibilities raging from ceramics to bio-based plastics.

It is possible to use bio-based plastics which degrade in an ambient marine environment, such as PHA or PHB, however, the rate of biodegradation in a marine environment is relatively slow. For example, it takes 1,5 to 3,6 years for a PHA bottle of 800 µm thickness to completely biodegrade, while increasing thickness the range of uncertainty and time required also increases (Dilkes-Hoffman et al., 2019). Therefore, for large, thick structures which need to show significant biodegradation in 5 years, PHA or PHB is not a suitable material.

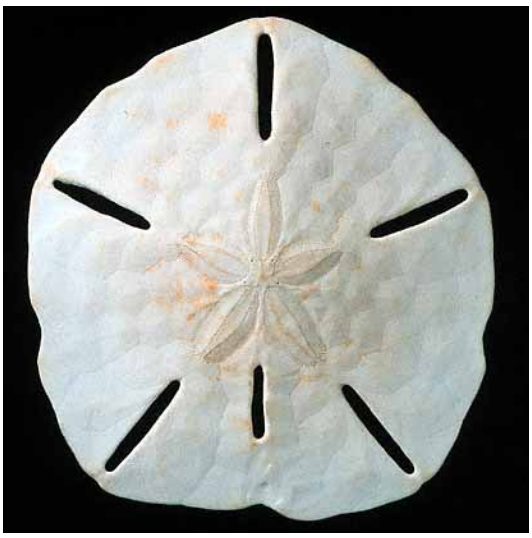


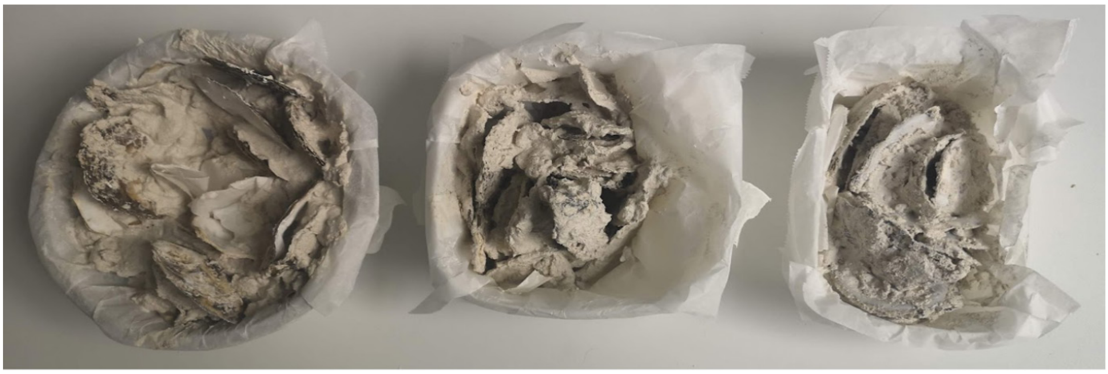
Figure 13: The sand dollar's skeleton with 6 holes called lunules. (Image credit: The Natural History Museum, n.d.)

For ceramics, materials with calcium such as gypsum, chalk or limestone can be very useful for oyster formation and growth, because calcium carbonate is one of their main shell-building materials (Yoon et al., 2003). Oyster larvae have also shown a preference to settle on surfaces which have a high amount of calcium because it resembles the chemical composition of shells, mostly preferred were empty oyster shells, lime or clay (Colsoul et al., 2020). One of the possibilities is to use BESE-reef paste, which comprises 80% ground shells and 20% bio-based binding additives (BESE products, 2021).

Testing the BESE-reef paste

BESE has provided a sample of reef paste and the small-scale structures made of oyster shells and this binder could be tested (Figure 14). Three different samples were used to test different binder application techniques (Figure 15): applying the binder on top of the shells or mixing shells and the binder together while differing the paste viscosity. Samples were weighed (before paste application and after) and put in the room temperature (~20 °C) environment to dry and set. After 10 days all samples were dry: samples

Figure 14: Various types of samples prepared for testing with BESE-reef paste. One of the techniques is to mix the shells with the binder.



a) Paste poured on top of shells | b) Shells mixed together with paste (lower viscosity paste) | c) Shells mixed together with paste (higher viscosity paste)

Figure 15: Prepared samples with different application methods.

B and C were brittle and shattered shortly after taking them out of the moulds. Sample A was stronger and could retain shape, but after several handlings, it shattered 15 days later as well (Figure 16).

This test provided some important insights and showed the challenges if this design direction would be chosen:

- **Weight:** Sample A (dimensions: ⌀=22 cm, h=8 cm) weight increased almost 2 times after the reef paste was applied and dried (Figure 16). Large-scale shapes (⌀=70 cm, h=30 cm) could weigh around 44kg, which could pose challenges for handling & transportation.
- **Brittleness:** All samples were brittle and shattered within 15 days with minimal handling. That might be due to the microfractures in the binding matrix. Structures should withstand stresses when being deployed to the sea, the brittleness of this material poses a challenge in an offshore environment where quick handling and time effectiveness is essential.
- **Biodegradability:** both shells and BESE-reef paste are made of naturally occurring materials based on calcium carbonate. In addition, the reef paste also biodegrades in a marine environment. These materials are both beneficial to oysters and other marine life, and they do not need to be taken out once the legal permit period has ended.

While the material composition seems to be beneficial for benthic growth, the binding material is too heavy and too brittle to fulfil design requirements for handling during offshore deployment. Weight could be decreased by adding more shells to the structure, but this would further increase the brittleness. By using reef paste in this way, the concept runs into the inevitable limitations of calcium carbonate-based materials being heavy and brittle.

Shells bound with external structure

The second direction was inspired by the current approaches from ARK, other reef restoration organizations and oyster farms (Figure 18). Often young spat on shell are put into the oyster crates or meshed metal wire boxes which keep the oyster shells together. Similar to the oyster reef (Figure 17), packed empty oyster shells create surface irregularities and gaps which reduce predation opportunities. To prevent sedimentation, structures are raised from the seabed by hanging them on the line or by adding the legs. From the prototype analysis (Chapter 2), it is known that the ARK model (Figure 18b) was challenging to deploy, required a lot of manual assembly time, and the legs were unstable so could not be moved, once the structure is assembled, units had to be deployed one by one, taking care that they land in a correct position.

To solve challenges related to deployment with ARK's model, new design possibilities were explored with new aspects:

- **Connected units:** by connecting the units either in a row or in a cluster and deploying them all at once, deployment time is drastically reduced, less manual labour is needed, and the system can be further automatized. The inspiration comes from the first iteration (Figure 19) and from the technique used to catch lobsters in the North Sea (Figure 20).

Figure 19: Cluster idea from the first iteration: separate units forming a cluster.

Figure 17: Natural Pacific oyster reef. (Image credit: Wilker (2010).

Figure 20: deploying cages to catch lobsters. All cages are connected in a rope and deployed in a row.

a b

Figure 18: Various structures used to keep oyster shells: a - oyster baskets used in oyster farming, b - one of the prototypes developed by ARK using metal wire mesh to pack empty oyster shells. (Photo credit for figure b - Ernst Schrijver, ARK Rewilding Nederland).

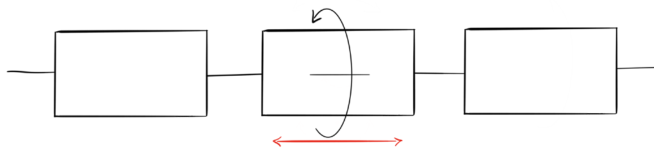


Figure 21: When units are connected in a row and pulled towards the seafloor, they will rotate mostly on the longitudinal axis. Other rotations are minimized.

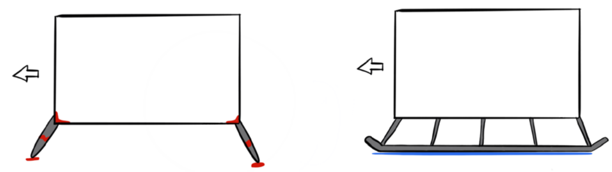


Figure 22: Different support legs can impede or facilitate sliding on the surface.

- **Limiting rotation axes:** When units are connected in a row and pulled from the deck of a moving ship to the seafloor, they will rotate mostly around the longitudinal axis when falling onto the sea floor. Lateral and vertical rotations are minimized due to the tension between the pulled units. Therefore, only the longitudinal axis needs to be considered when designing support structures to raise the unit from the seafloor.
- **Sliding:** If the units would be deployed in a row, pointed legs from the current design would increase the friction on the deck surface and could break off when being pulled. Instead, the support structure could facilitate sliding on the deck like a sleigh (Figure 22).

Scale model

A scale model of one unit was made (Figure 24) to test out the assembly and understand possible construction or manufacturing challenges.

The oyster gabion model houses spat on shell while being raised by the support structures. The cradle protects the young oysters from predation, at the same time, support structures raise it from the seafloor to protect oysters from sedimentation.

The support structure is designed to function in any longitudinal rotation position – no matter how much cradles will rotate around the longitudinal axis before falling onto the seabed, the supports will always raise them 200mm above the seafloor, see Figure 25.

The shape of the support structures is similar to a sleigh, which facilitates sliding. Moreover, the outline for each support wing is bent to minimize surface area in contact with the ground as well as strengthen the support wing against compression from oyster cradle weight. Bending the outline outwards distributes the compression stress more

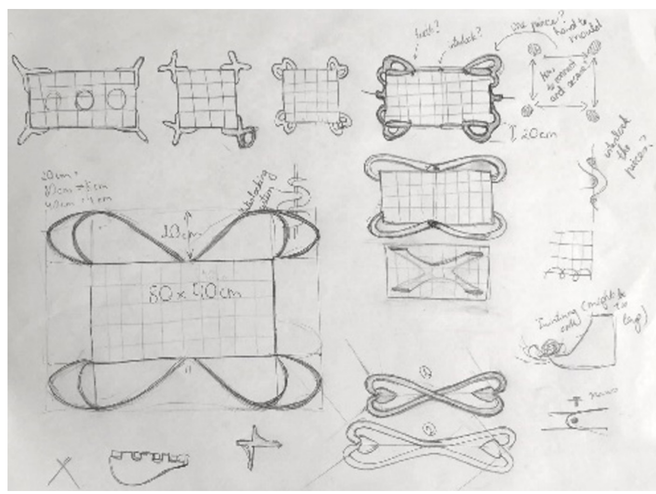


Figure 23: Sketches of shape and concept exploration.

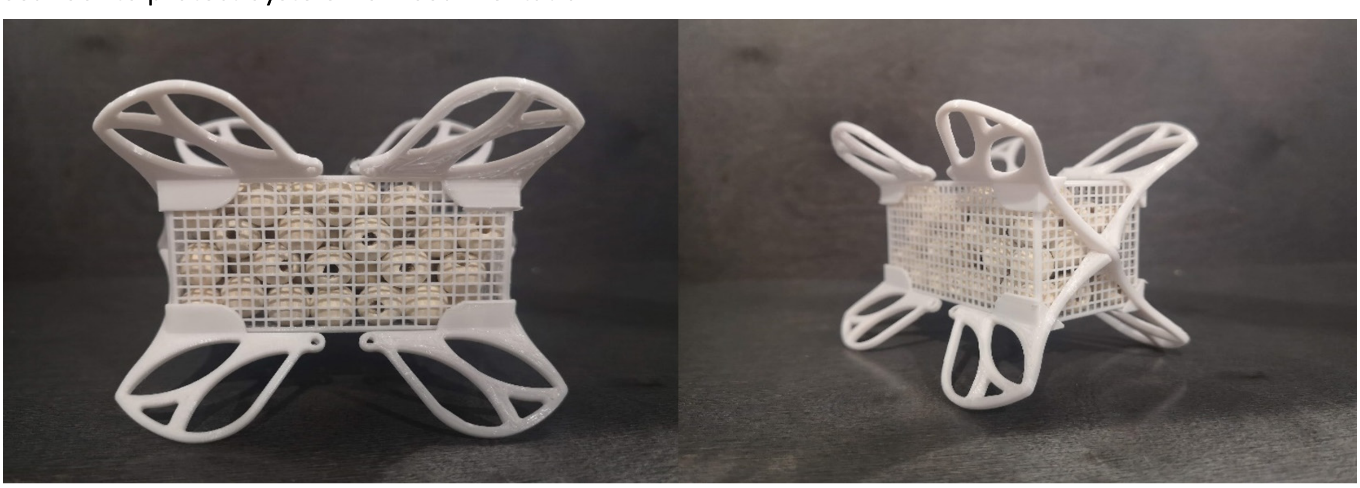


Figure 24: A scale model for a design direction with a structure holding the oysters.

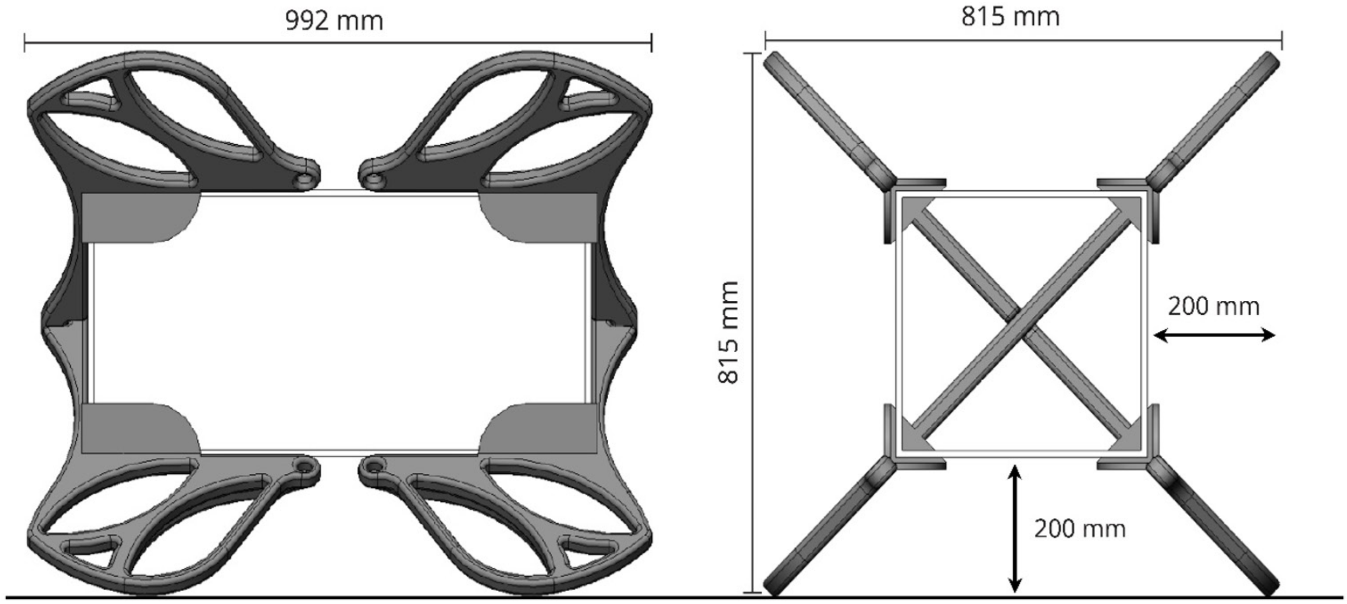


Figure 25: General dimensions of the design. No matter which longitudinal side the structure falls, it will always be raised 200mm from the seafloor.

uniformly and does not block the sliding movement if any surface irregularities or bumps are met along the way. The inner wing surface was cut out to mimic the sand dollar strategy (Figure 13) to act as water current-drainage places to stabilize the structure. In addition, these holes help with minimizing the weight, the place for inner structural lines could be arranged according to typology optimization to further reduce the weight but retain the needed compression strength.

Assembly is made easier due to the interlocking part between four support legs (Figure 26) with the same method on the other side.

However, during model creation, printing and testing main challenges for this concept have been indicated:

- **Material use:** for an 800x400x400 mm gabion basket, the support structure will be large (Figure 25) and can become expensive due to the amount of material needed. This will likely inhibit the scalability. Therefore, further ideation should look into the way to minimize the support material while still protecting the oyster from sedimentation.
- **Manufacturing:** due to their 3d geometry (corners holding the oyster cradle), the support structures are more complex to manufacture, they would need either more complicated moulding shapes or additional steps in manufacturing to attach the inner corners for the cradle. This will likely raise the price-per-unit and will inhibit scalability from an economical perspective.
- **Assembly**: even though the supports are assembled easily, the support sides need to be tightened together with ropes or belts. Tightening all four sides will require more time for manual labour during assembly on deck. This will have negative effects on scalability, due to economical and temporal reasons, and can become even more challenging if the sea is not calm and the ship is moving excessively.


Figure 26: The interlocking mechanism for one support side.

Material

The materials used for the oyster crates vary according to their use case:
Oyster farmers often use baskets (Figure 17a) made of polypropylene for the off-bottom farming method: baskets are attached to a line and repeatedly retrieved and used again for multiple seasons. While this material is non-toxic and effectively used in aquaculture, it cannot be used for structures designed to be left at the bottom of the sea, because polypropylene is not biodegradable and will add to the problem of marine plastic pollution.

Steel wire mesh can be used as well (Figure 17b) because carbon steel comprises non-toxic elements of carbon and iron. However, these meshes are usually galvanized (coated with a layer of zinc) to protect the mesh from corrosion and increased concentrations of Zinc or Zinc Oxides can negatively affect various marine organisms (Sarker et al., 2021; Yung et al., 2014). Therefore, if the steel mesh would be used in the new design, it should be a bare carbon steel mesh without any corrosion protection layers to limit the ecotoxicity in the marine environment.

APPENDIX B: CONCEPT EXPLORATION – PROCESS AND INTERIM IDEAS

1. Oyster nets

Several ideas and iterations have been explored of how biodegradable oyster bags could be used in a large-scale oyster reef restoration project.

Figure 1: BESE oyster bag made from a biodegradable biopolymer. Image credit: BESE products, 2022)

1.1 Oyster nets with support frames

One of the possibilities is to design frames which could be attached to the chain right before it is deployed to the sea. The frames could be attached where the knot is placed by the deployment personnel on the ship deck. Small-scale prototyping (Figure 2) has provided some valuable insight:

Advantages:

- Very easy and fast support assembly, personnel on the deck would just need to slide the support into the chain where the knot is placed.

Disadvantages:

- Attaching frames to the flexible structure makes them unstable and they do not raise oyster bags efficiently (Figure 2). To stabilize these supports, additional stabilizing elements and attachment should be introduced to the assembly which negates the initial ease-of-attachment advantage.

Another possibility is to attach the support structures to the bags. When the bag is filled with oysters, it becomes less flexible and can offer a more stable basis for the frame. In addition, when on the seafloor, the raised bags would remain straight without falling on one of the sides because each bag is pulled and tensed by other bags. A prototype (scale 1/10) was tested out in the lake to see how it is affected by multiple deployments into the water (See Chapter 5, "Testing"). The support structure effectively raised the oyster bags from the sand floor but after a few additional drops, some frames started to fall off and the oyster bags ended up on the sand floor. With insights gathered from prototyping and testing activities, the last improvements were made: teeth on the inner right were introduced to grab and secure onto the oyster net tighter, inside the frame, patterned infill has strengthened the frame, the whole frame was enlarged a bit (Figure 3, Figure 4).

Advantages:

- Test has shown that the frame raises oyster bags from the sand floor.
- Frames are lightweight and easy to assemble – the first iteration design was one piece which needs to slide onto the connection point between two oyster bags. More stable

Figure 2: First oyster bag frame iteration.

frame designs are divided into two parts which surround and squeeze the oyster bag. Teeth introduced in the last iteration provide the best grip and stability.

- Efficient use of space – all frames can be stacked on top of each other to save space during transportation. Without the frame, units with oyster shells also are space efficient in the hatchery or during transportation.

Challenges:

- Complicated and expensive frame manufacturing - if frames would be laser cut, a lot of material would be lost. If frames would be made from steel beams and welded, the welding and bending process would be complicated and expensive.
- Frames inhibit the sliding - due to their attachment method, the frames are perpendicular to the sliding direction of the whole oyster bag row. Therefore, sliding this assembly from the deck would not be a suitable method. Unrolling or specific deployment structures would need to be built to facilitate easier deployment.
- The hexagonal frame shape saves some material use compared to the rectangular shape. However, the assembly is less stable underwater and if currents are perpendicular to the assembly row, it could start rolling.
- Narrow frame edge can get buried in the sand quickly. This will reduce the distance between the bags and the sand floor but stabilize the structure from rolling away.

Figure 3: oyster bags with frames from two iterations, on the left - frame which was tested in water, right - improved frame.

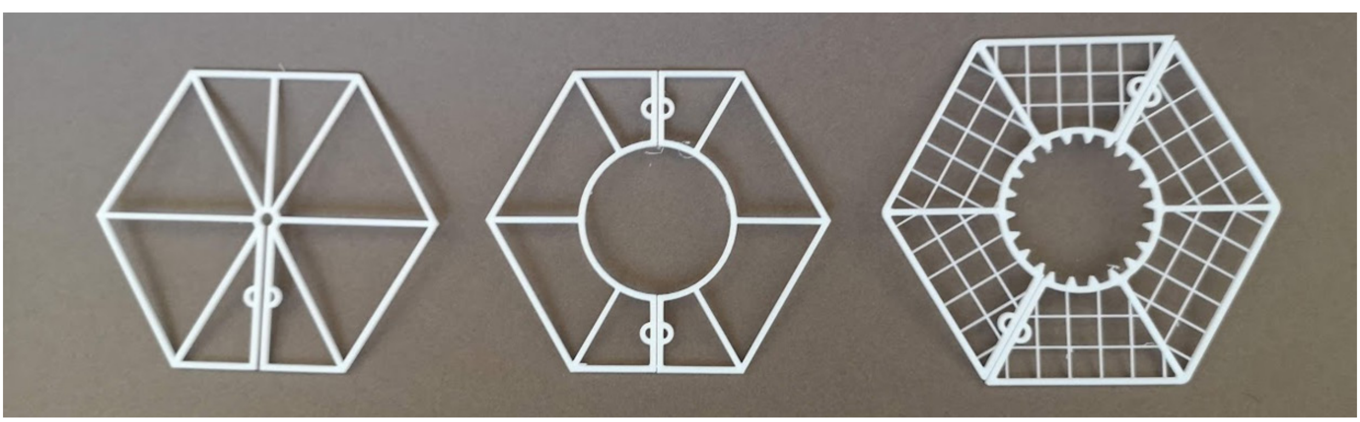


Figure 4: All support frame iterations: on the left- the first frame attaches to the knot, the middle - frame attached to the bag, right – an improved frame attaching to the bag.

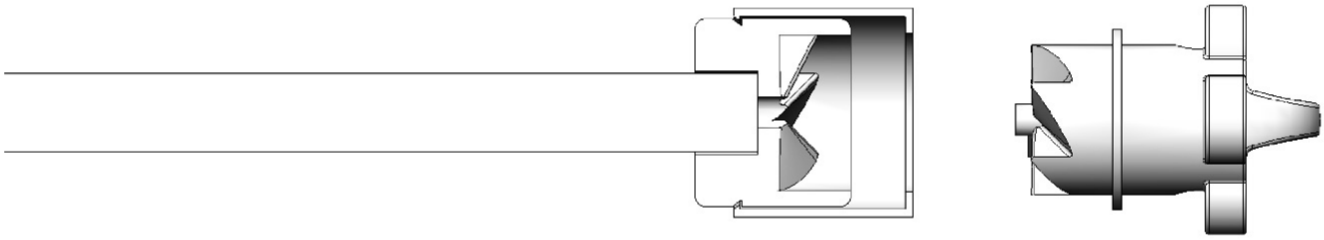


Figure 5: 3D model of the wind-up lock which mimics a common click pen mechanism. It is possible to twist and wind up the frame in one direction, but the frame cannot unfold because the ladder is blocking a rotation to the opposite side. The lock can only be released when the head (on the right) is pulled away from the groove (on the left).

1.2 Oyster nets with unfolding frames

Instead of the necessity to attach the frame manually right before deployment, the frame could unfold automatically when it is needed. By mimicking the basic clicking pen mechanism (Figure 5) it is possible to twist the frame around the oyster bag and lock it (Figure 6). A frame will unfold automatically when pull force is applied to the ends of the bag (Figure 7). The bags with a winded-up frame would be stored in a roll, when a chain of these bags is unrolled into the water, every few seconds the roll stops and certain bags' edges are pulled due to inertia. The pull force releases the lock mechanism, and the frame unfolds right before entering the water. No active human intervention would be needed during the deployment.

After low-fidelity prototyping, several insights can be highlighted.

Advantages:

- Idea has the potential to become a fully automated oyster deployment solution with a human intervention needed only to assemble the frame ends and to check deployment procedure quality. This would greatly improve deployment speed.
- With most preparation work done on land, much fewer personnel are needed on the vessel itself, which will reduce deployment costs.

Disadvantages:

- Mechanism is complex and would be produced with injection moulding, in the best case from biodegradable plastic. Injection moulding only makes sense in large-scale production. For medium-scale production, the costs of manufacturing would be too expensive to

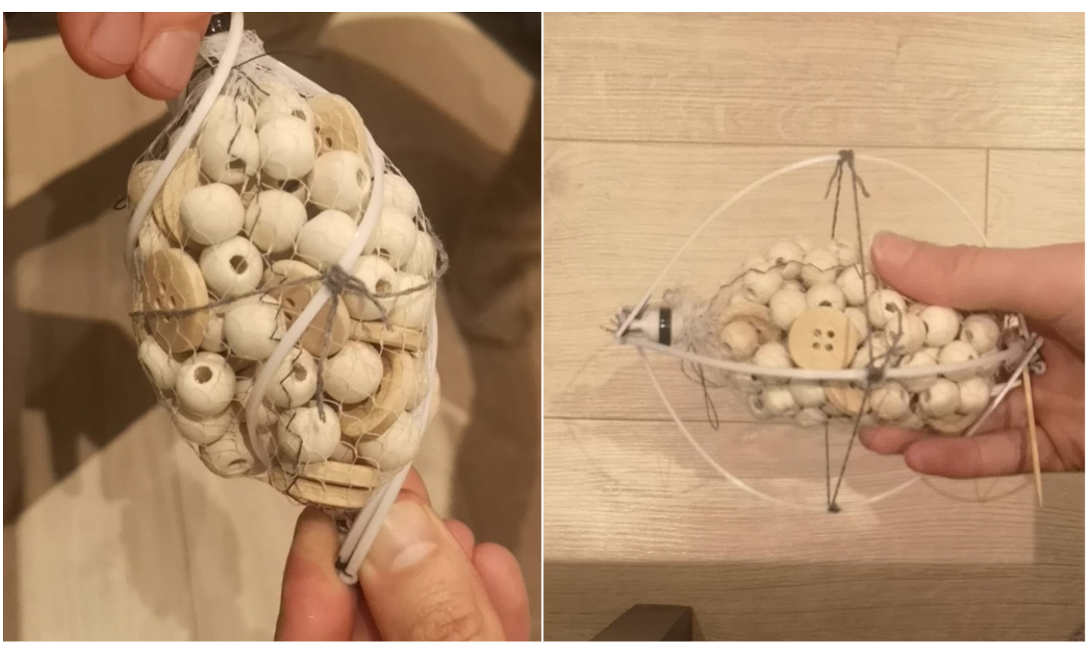


Figure 6: Prototype for the unfolding frame. Left - the frame is winded up around the oyster bag, right - once the mechanism is pulled, it releases the frame and it unfolds like a spring.

make it a viable solution.

- Unclear how to manage the balance between frame beam stiffness: the beams should be stiff enough to raise the oyster bag from the sea floor, but also flexible enough to be winded up around it. In the current prototype, the beams are not stiff enough to raise the structure from the surface but can be twisted around quite easily.
- Large winded-up structures can be dangerous for people around them, similar to numerous large and loaded springs, these structures can unfold with great force and cause accidents if they do so at the wrong moment.

2. Gabion baskets

Several ideas and iterations have been explored of how the steel frame gabions could be used in large-scale oyster reef restoration projects.

Figure 7: gabion baskets used for oyster reef restoration. Image credit: EnZar (n.d.)

2.1 A single gabion

For this iteration, the main goals included minimizing the material use and reducing the costs of manufacturing while maintaining the aforementioned functions. The process went as follows:

Firstly, supports were adjusted to secure to the wall instead of the corner which would rotate the gabion 90 degrees and it would sit on the edge at the seafloor (Figure 8). Designs from the first and second iterations were compared: In the rotated design, material use for supports is reduced by 38% and geometry is simplified by taking out the corners. Overall object volume is reduced by 43%, which allows better stacking on the deck. Due to a part of the gabion touching the seafloor, some oysters would get sedimented and suffocate. For a fair comparison, it was calculated that oysters below the 20 cm line will be lost. According to the theoretical calculation: in the first design the survivability would be 100%, while in the second design – 80%.

Another idea was to reduce the support material even further by attaching support just on one side (Figure 9). Compared to the first design, material use is reduced by 69% while losing 20% of oysters to sedimentation. In addition, a one-sided design reduces steps in assembly on the ship deck, which would save deployment time on a ship deck and structures can be connected in a row (Figure 10, Figure 11).

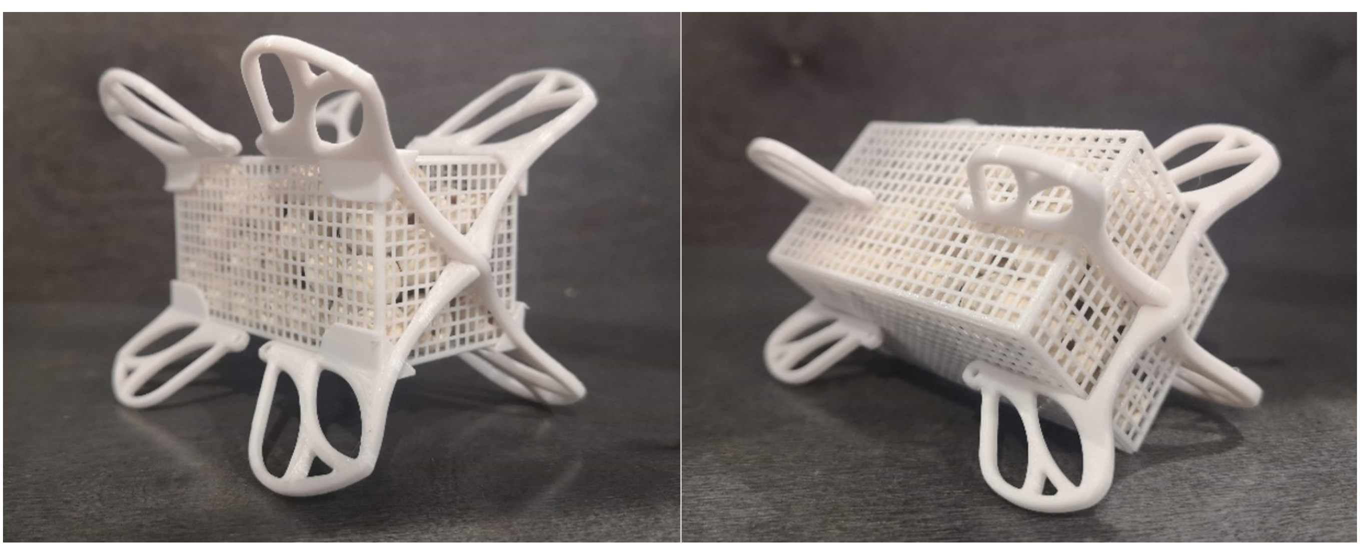


Figure 8: different ways how support structures can be created: on the left – a design from the first iteration, on the right – a design with reduced material use for the support structure.

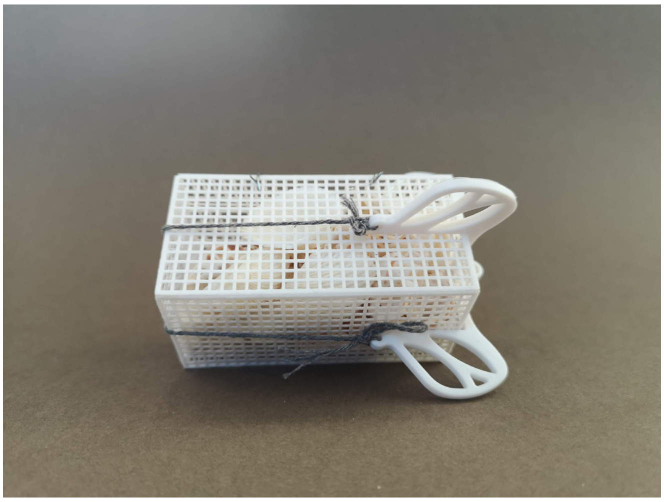


Figure 9: One-sided support design.

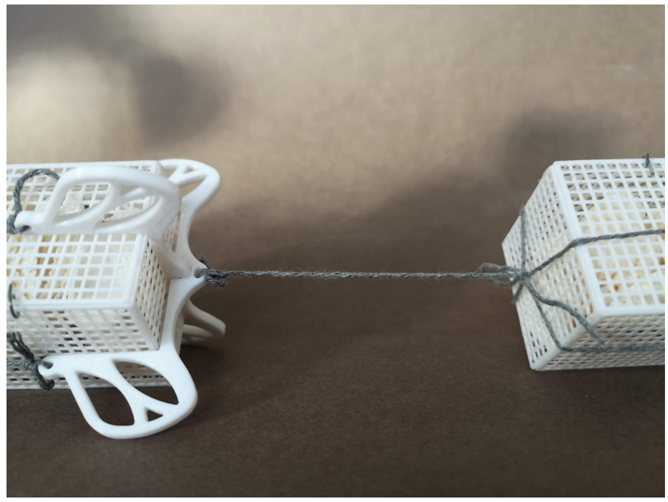


Figure 10: Connection between two units.

With one-sided support, the structure might fall into a less desirable position with a front gabion edge and one support structure touching the seafloor (Figure 12). It was calculated that this position would increase the oyster loss: 24% loss compared to the desired position (80% of survival). A test session was done with 1/10 scale models in the lake with a foam sheet as a boat to determine the most likely fall position and possible deployment scenarios (see Chapter 5, "Testing").

Last support iteration focused on reducing oyster loss by enlarging the support structures. The topographic optimization method was used with a 2D TopOpt app (DTU & Aage, 2020) (Figure 13). Shape suggestions were translated to a scale model (Figure 14) and this design is compared with the first iteration (Figure 16).

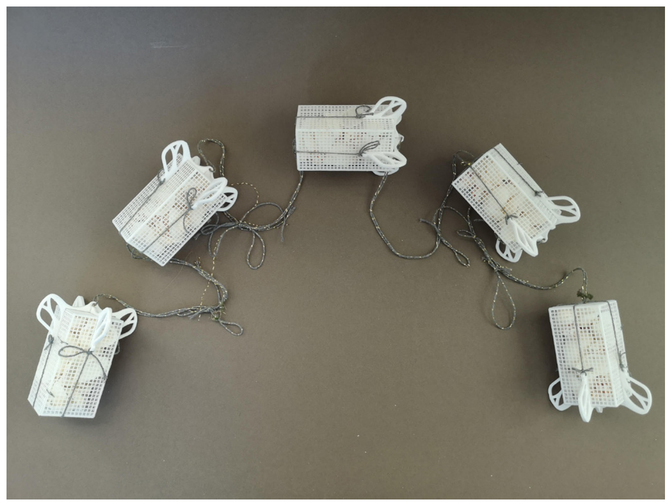


Figure 11: Units connected in a row, while testing deployment arrangements.

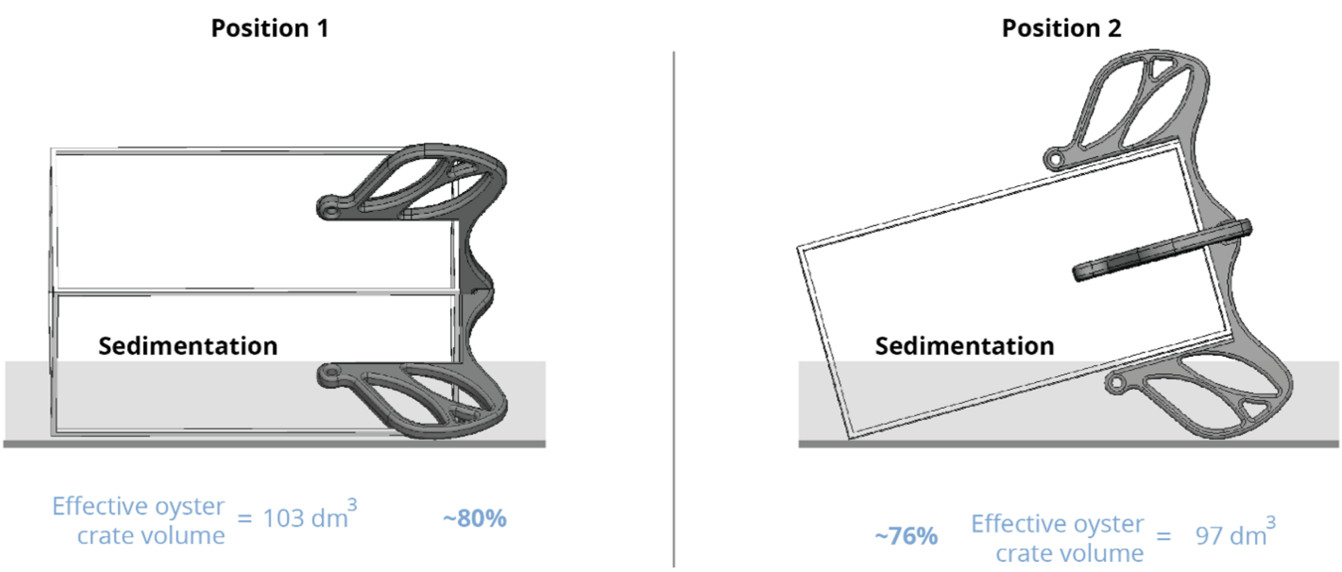


Figure 12: Comparison of the different positions on how the structure can fall on the seabed.

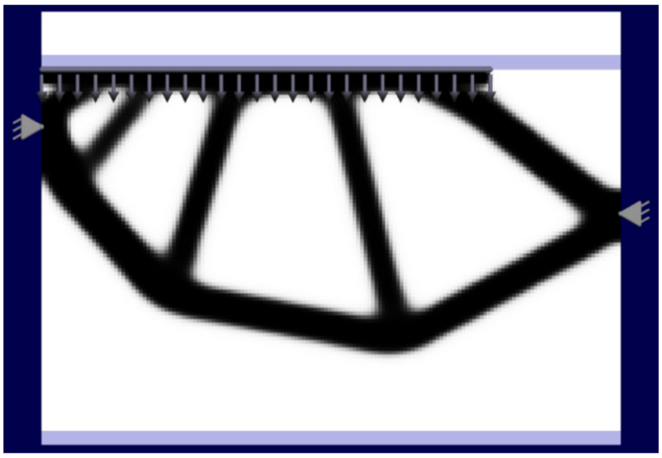


Figure 13: Silhouette developed by a 2D TopOpt app.

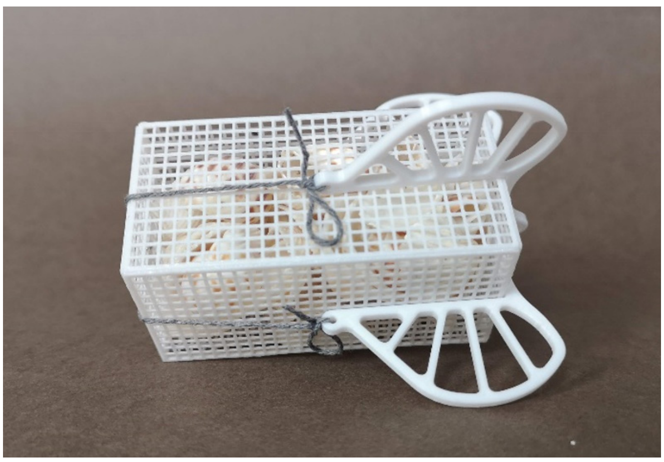


Figure 14: The last support iteration.

According to the ergonomic and technical requirements, gabion measurements can be adjusted (Figure 15), for further support development gabion size of 400x400x800 mm was chosen due to optimal size while handling and minimizing the use of steel per oyster batch. Gabion size is to be adjusted according to support design and further ergonomic requirements.

Advantages:

- Material use is drastically reduced: 4^{th} iteration uses 68% less material than the initial concept with fewer manufacturing steps and easier assembly.
- Easy assembly on the ship deck or land: The base is connected in a cross structure, then the gabion is placed into the support, the gabion and support legs are tightened with a rope, and the unit is rotated sideways and connected to another unit.
- Simple geometry with an interlocking mechanism does not require using other fastening equipment or tools for support assembly.
- Structures are designed in a way to facilitate easy sliding of the deck in the longitudinal direction.

Disadvantages:

- 16%-20% of oysters would be lost if the latest support design is used, compared to 0% with supports from the first iteration. Supports would need to be enlarged drastically to further reduce oyster loss.
- Structures are complicated and expensive to manufacture, especially when using non-toxic material possibilities.
- Tests have shown that for structures to fall in an upright position, a large distance between the modules is needed – more ropes, more possibilities for entanglement and possible danger on the deck.

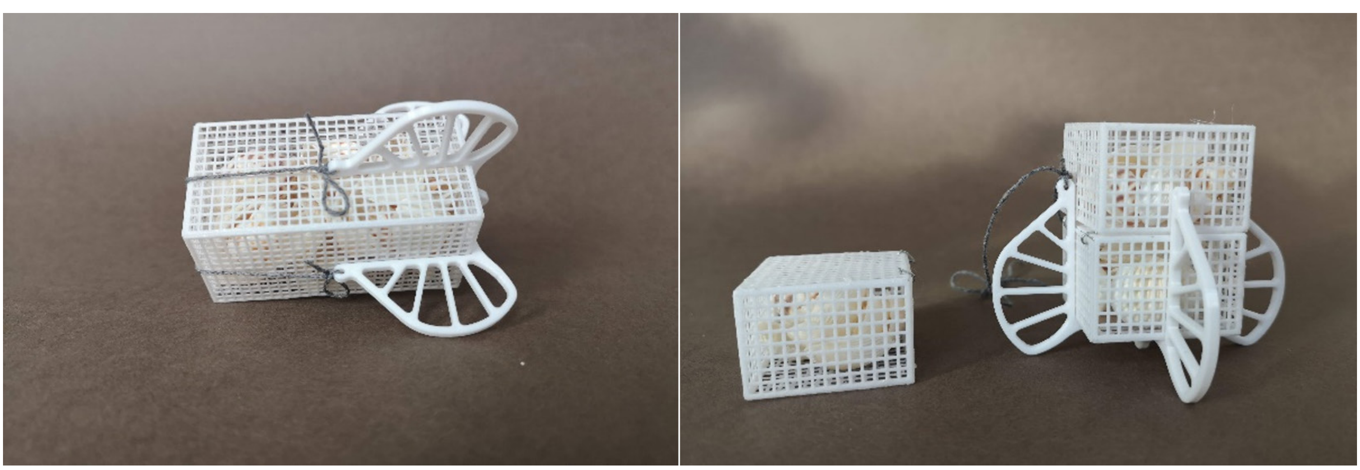


Figure 15: Few design ideas for using different gabion sizes for unit weight reduction due to ergonomic requirements.

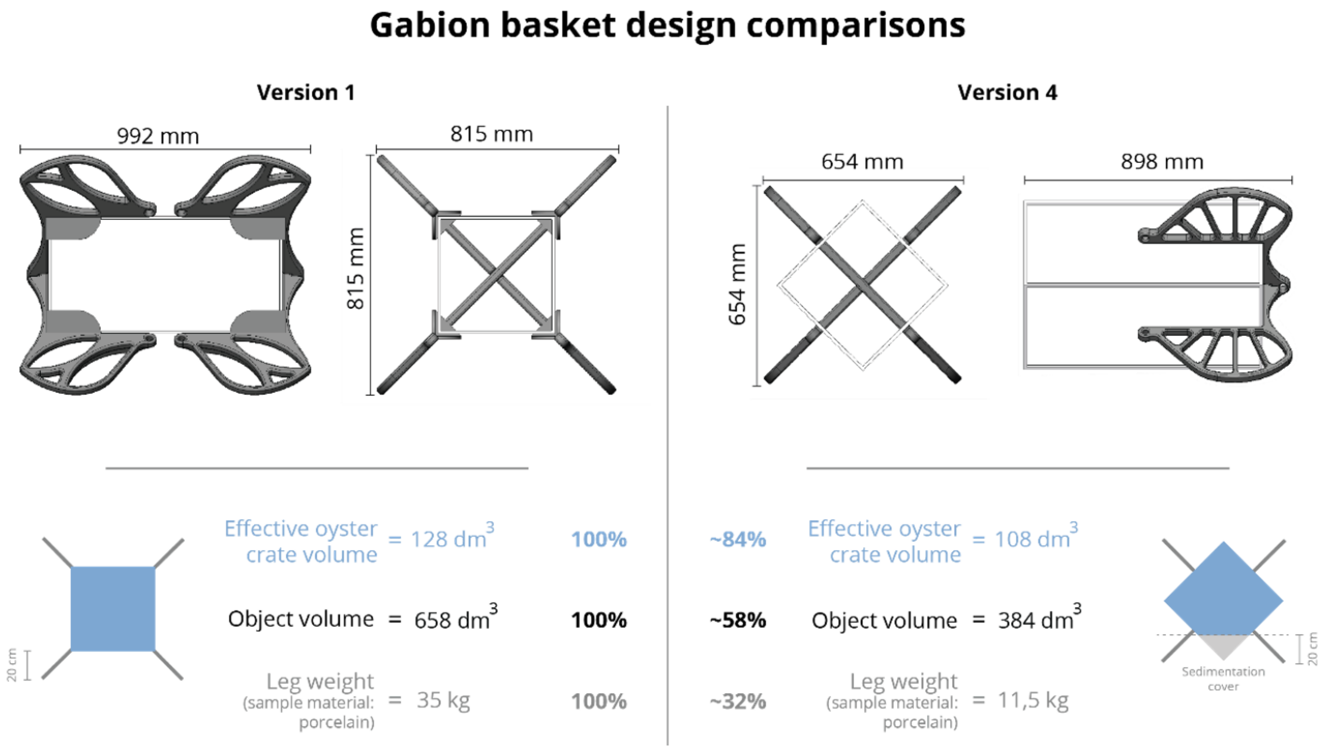


Figure 16: Comparison of support structure designs: on the left – a design from the first iteration, on the right - structure from the fourth iteration.

2.2 Gabions connected together

There is also a possibility to connect two gabions together on the edge to make a double diamond shape (Figure 17). In the case of 400x400x800 gabions, the diamond shape would already lose fewer oysters to sedimentation: with 20% under the 20cm line of possible sedimentation, compared to 50% if the gabion baskets would be just thrown out and land on one of the faces. The structure is also deemed more stable in comparison to a single unit - it is wider and will resist stronger water currents without tilting. Surface complexity is enhanced because two gabions introduce the bottom hole, several corners, and gaps between each module, where various fish and other marine organisms can grow and live.

Because the middle edge connection already holds gabions in desired diamond position, the support structures can be designed to raise the gabions more efficiently and save more oysters from sedimentation. A few support structure designs have been explored and will be discussed further.

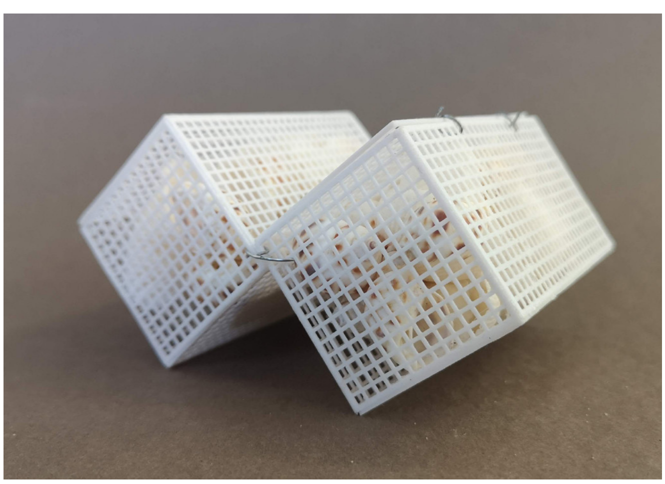


Figure 17: Double diamond shape when two gabions are connected.

2.2.1 CNC frame

One of the possibilities is to use a support frame which would raise the gabions from two sides and ensure that the whole structure falls or tilts on those desired sides. The top and bottom frames are identical, making them easier to manufacture and assemble. Deployment would remain the same: connecting the pair together and then connecting multiple pairs in a row to reduce rotation axes. By implementing grooves and bumps on the support parts, the gabions are secured from sliding off the structure (Figure 18).

Advantages:

- Assembly is quick and simple. Firstly, the bottom frame is assembled from 4 parts. Then two gabions are placed into the designated grooves and connected together. The top frame is assembled and put on top. All structure is secured from two sides with jute lashings and clamp buckles. The assembly is then connected to another unit and the row is formed.
- Effective oyster protection and higher survival rate. The frame protects gabions from impact and deformation during the deployment and raises them 140 mm from the ground which results in an improved oyster survival rate (97.7% above the 200 mm sedimentation line).

Challenges:

- Part geometry is complex, therefore, CNC would be the method of manufacturing and would cost around 30 euros per part (according to the quotes from the manufacturing facility in Amsterdam). Plywood is usually used for CNC manufacturing, but due to chemicals used even in formaldehyde-free types, it is not a suitable material to be left to decay in the marine environment. Another way is to CNC these parts from untreated solid wood planks, but the whole process becomes more expensive due to much more manual labour needed in preparation stage.
- Bumps designed to restrict gabions from sliding off might be too weak and could break off during the deployment, because of the wood fiber direction.
- When exposed to damp or weather dynamics environments, untreated wood parts tend to deform non-uniformly, making the frame fit less predictable.
- Unit may fall in two positions: upright – in that case 97,7% of oysters are above the sedimentation line, sideways – 79,7% of oysters are above the sedimentation line (Figure 20). Further testing should be done to determine what is the possibility the structure lands sideways.

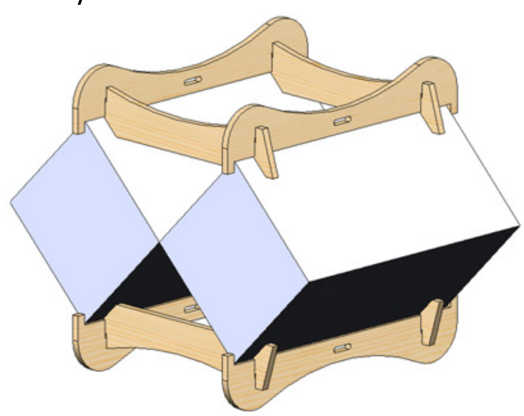


Figure 18: Gabions are secured with grooves and bumps to stay in place.

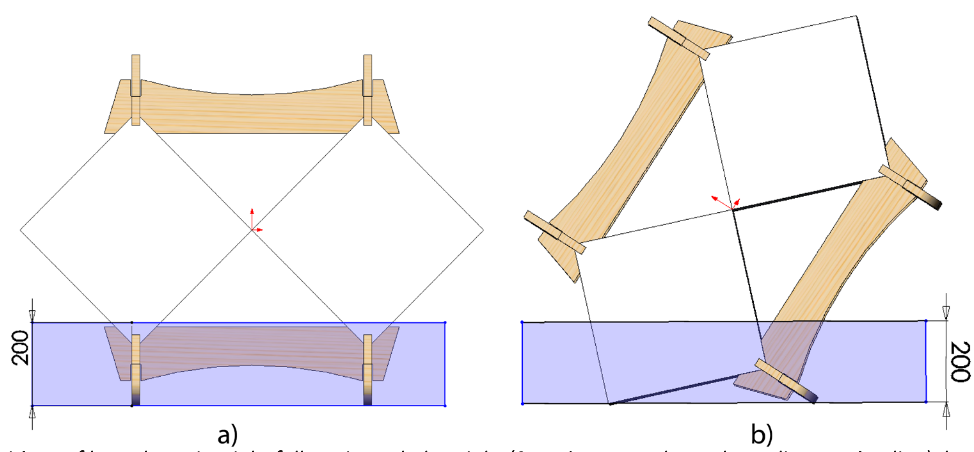


Figure 19: Positions of how the unit might fall: a - intended upright (97.7% oysters above the sedimentation line), b - sideways (79.9% of oysters above the sedimentation line).

2.2.2 Pallets

Another possibility is to use half-euro pallets or display pallets as a base to maintain the same functions as with a CNC frame.

Advantages:

- Pallets - durable and standardized: Different types of euro pallets are used in many logistics operations. They are designed to endure the rough handling process, manufactured from solid wood planks, the dimensions are on an agreed standard: 1200x800 cm - a euro pallet, 600x800 cm – half euro pallet with maximum load capacity for half-euro pallet being 500kg.
- Affordable: Pallets are used in almost every larger-scale logistics operation, the manufacturing process is highly automated, therefore the costs are relatively low: from 10 to 15 euros per pallet.
- High availability: As a standard, euro pallets are manufactured across Europe and used interchangeably. Pallets can be acquired from local warehouses or businesses reducing the need for long-distance transportation.
- Circularity: Various companies that focus on euro pallet repair. If necessary precautions are considered, used pallets can be deployed with this assembly as well. The main point of attention would be to ensure that they are not chemically contaminated.
- Surface complexity: Pallets have a relatively complex geometry with many corners, cavities and holes for various marine species to settle.

Challenges:

- Unit may fall in two positions: same risk of the whole unit falling sideways (Figure 21), which decreases the oyster survival rate (97,3% survival if the unit falls in a desired upright position, 84,3% survival if the unit fall sideways). Testing and evaluation need to be done to measure what is the probability of structures ending up in a sideways position.

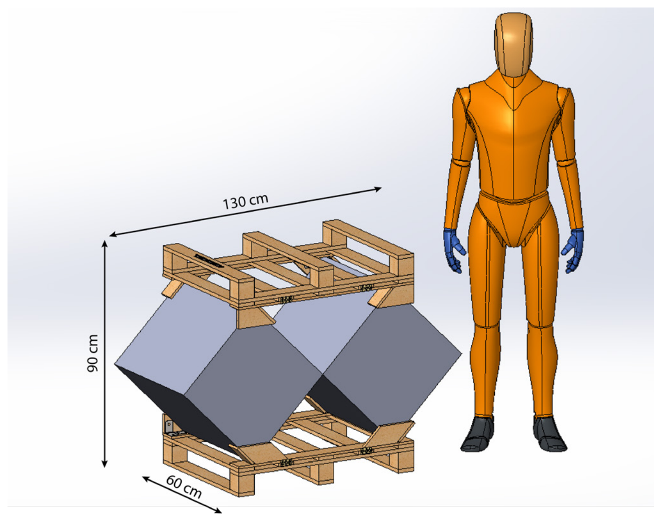


Figure 20: One of the pallet designs, one unit assembly.

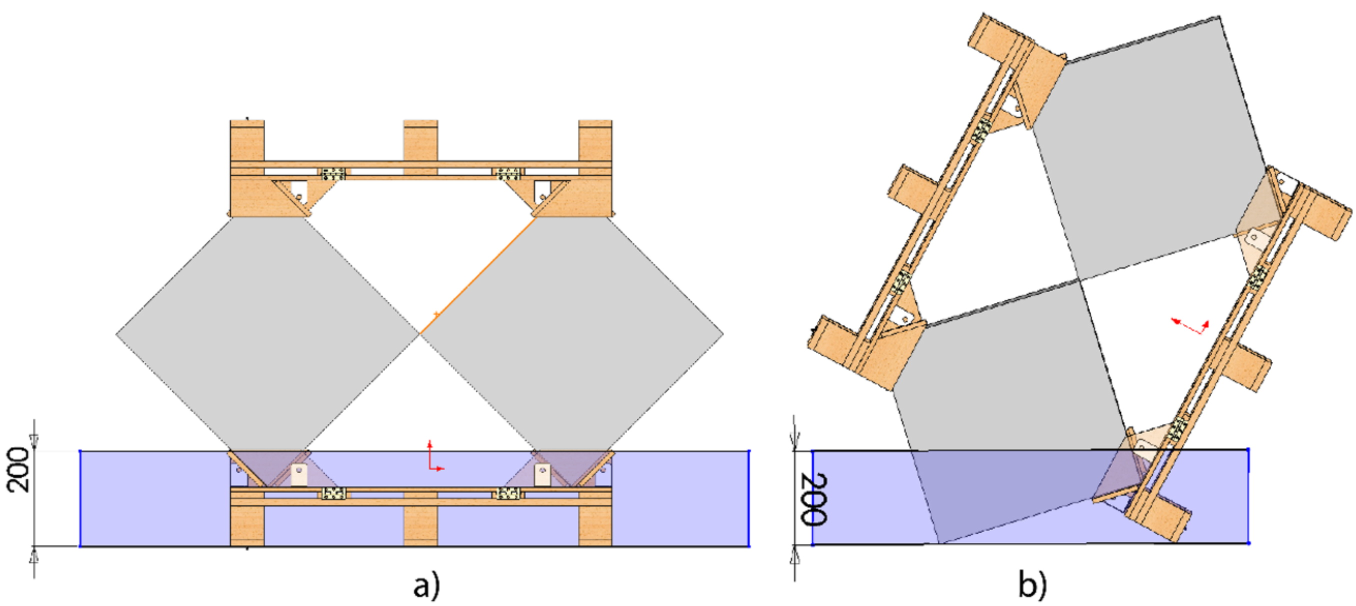


Figure 21: Two possible positions: a - desired upright positions (97.3% oyster survival), b - sideways position (84.3% oyster survival).

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: Motuzaitė
initials: J.M. given name: Justė
student number: 5393183
street & no.:
zipcode & city:
country: The Netherlands
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: Prof. dr. ir. Conny Bakker dept. / section: SDE
** mentor: Dr. Jeremy Faludi dept. / section: SDE
2nd mentor: Gwenaël Hanon
organisation: ARK Natuurontwikkeling
city: Nijmegen country: The Netherlands

comments (optional):

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 Prof. dr. ir. Conny Bakker date 13 - 09 - 2022 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: 32 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 28 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 C. van der Bunt date 16 - 09 - 2022 signature

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: ★ APPROVED ○ NOT APPROVED

Procedure: ★ APPROVED ○ NOT APPROVED

- explanation team members same section is missing

comments

name Monique von Morgen date 20 - 09 - 2022 signature

Design for biodiversity: enhancing biogenic shellfish reefs

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 12 - 09 - 2022

09 - 03 - 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, ...).

The North Sea used to be 20-30% covered in shellfish reefs, which provided important hiding, breeding and feeding spots for various species. Reefs are a crucial part of marine biodiversity: 60% more species occur on the shellfish reef than on sandy areas. However, intensive fishing with rakes on the seabed has eliminated most of them and now most of the North Seabed comprises just sand.

One of the key species for The North Sea reef ecosystem is the Flat oyster. As ecosystem engineers they create reefs by attaching and growing to solid structures, which for other species provides food source, shelter from high-speed currents and predators. However, because of the flat seabed in The North Sea, the underwater currents are much stronger, there is no hard surface for shellfish to attach to and create new reefs. This poses a looped problem: shellfish cannot cling to the seabed and start forming the reef because there are no natural structures, such as reefs, which would slow down the currents and provide a solid base to attach. In this degraded ecosystem, and intervention must be done to encourage more drastic ecosystem regeneration.

ARK Nature (“ARK Natuurontwikkeling”) is an organization working on rewilding the Netherlands, focuses on land and marine ecosystems regeneration as well as education on rewilding. Ørsted is a Danish renewable energy company competing in the tender to build an offshore windmill farm off the Dutch coast. Together they are starting a Marine Field Lab in the Dogger Bank, which is a shallow part on the northern boundary of the Dutch North Sea to test out solutions for marine ecosystem regeneration. ARK Nature will search for ways to rewild The North sea by 'kickstarting' the ecosystem with the key species of flat oyster to form biogenic reefs. They are looking into development of structures which could be deployed onto the North Seabed for shellfish to cling on and start growing. In the future offshore windmill farm in this case will provide a crucial 'no fishing' zone – a refuge for the shellfish reefs to grow and become hotspots for marine biodiversity. In addition, collaborating with Ørsted would bring down the operational costs of deploying and maintaining the reef formation solutions as the maintenance of the windmills and the reef formation parts could be done with the same ships.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Shellfish reef in Voordelta (Source: ARK Nature).

image / figure 2: Suitable circumstances for shellfish reef formation.

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.

When stable structures are introduced to the North Sea waters, various species of shellfish can cling on and start growing. The reef can start forming on these structures and grow further while creating a suitable habitat for a wide array of other marine species. After interviews with ARK Nature team, several major challenges were noted:

First, rewilding of the North Sea needs to cover large areas to reach notable positive impact, from hundreds of hectares to tens of km2. This kind of large-scale project faces cost and time limitations. Currently, there are numerous different designs which are aimed to encourage reef formation. However, most of them are expensive or slow to manufacture, or, more often, require too much deployment time and resources. Therefore, when trying to work on a large scale, current solutions become unviable. Creating structures for large scale deployment by minimizing the manufacturing costs and deployment time poses the biggest challenge.

Secondly, due to legal certification requirements, structures which are deployed in the North Sea to support reef formation should be installed there temporarily. Structures should either become the reef itself, dissolve in the sea water or be taken out. In the first case, the biomass should grow over the structure. In the second, the structure needs to provide a solution for shellfish to attach for a suitable amount of time while slowly dissolving in the water leaving only the natural reef formed in the future. In last case, the structures should be retrieved from the seabed, however, this imposes additional costs of using the ship with the crew, which can easily turn into financially unviable solution. In all cases, the material which the structures are made of should be biocompatible, because living ecosystems will be growing on them. In addition, if the structure dissolves, special attention should be given to which chemical components are introduced, to not negatively alter the chemical composition of the sea water.

Third, if the reef starts forming on the windmill, after 20-30 years the reef ecosystem will experience major, if not destructible, disturbances due to windmills being dismantled and/or changed. Therefore, the reefs should form on the sea floor in the space which would not be altered, for example between the windmills and outside of the wind farm, to avoid being destroyed.

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.

Design structures which could provide suitable environment and conditions for key species of shellfish to enhance the biogenic reef formation in the North Sea, within and outside of the offshore windmill farm.

I aim to design a product, a structure, which could be used to enhance the shellfish reef formation. The structures should: Create suitable conditions for the key species to grow and form the biogenic shellfish reefs in the North Sea; Reduce the bottom sheer stress to aid biogenic reef formation; Be scalable for big volumes in terms of offshore deployment speed and price; Have temporary lifetime due to legal certification - should dissolve gradually or become a reef itself and should be biocompatible with the sea environment; Form a standalone reef.

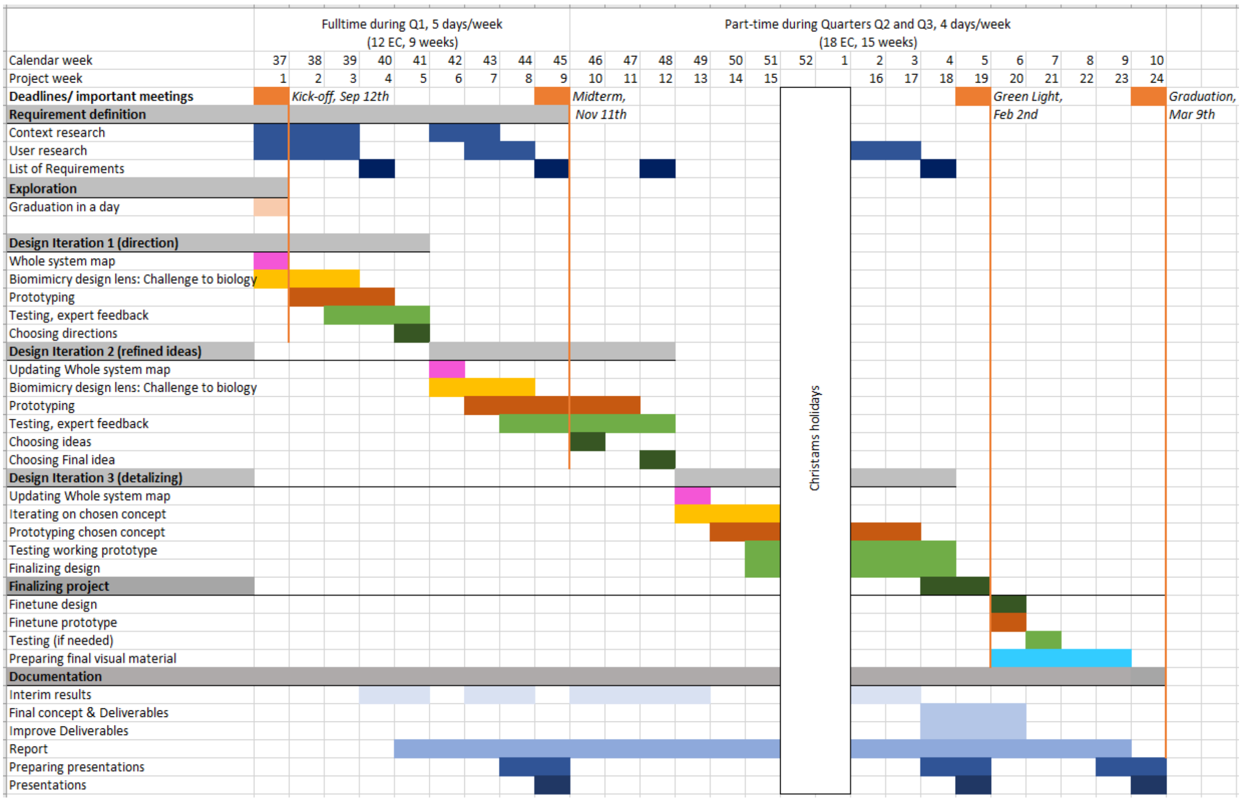
The graduation project aims to answer these research and design questions:

1. Feasibility & desirability: How to design structures that actively enhance the biogenic reef formation in The North Sea? Sub-questions consider how to: stabilize structures on the seafloor, effectively reduce the sea current speeds and make material and structure selection according to ecological and deployment factors.
2. Viability: How to scale up the design in terms of quantity of hundreds of hectares or even tens of km2 of The North Sea? Sub-questions consider how to: integrate the structures into the whole production process (from the oyster hatchery to the North Sea site), minimize manufacturing & deployment price and time, use standard equipment and materials to deploy these structures in offshore sites.
3. Success: How to measure the success of the design, in terms of effectiveness, usability and scalability? For effectiveness, measurements will be done to validate whether the structures can hold a heavy current and test how they handle the sediment flow and dynamics around. For usability, ease of production and possible deployment time as well as worker safety will be evaluated. For scalability, manufacturing and deployment price will be calculated.

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 12 - 9 - 2022   9 - 3 - 2023 end date



I am taking the research through design approach where design directions guide the attention to necessary research topics and expert feedback for successful product development. The project will go through three major iterations, while narrowing down the solution space with each:
1. First iteration, focused on several different directions, directions will be embodied with low-fidelity prototypes that will be used to gain feedback from experts. Working or deployment principles could be tested on an abstract level.
2. Second iteration, focused on one design direction, ideas are prototyped in higher fidelity already reflecting the more detailed working and deployment principle. Testing structure stability and effect on water currents, expert feedback.
3. Last iteration, focused on detailing design, producing, and testing a working part of the structure for effectiveness (performance in water) as well as usability (worker safety, ease of handling and deployment speed).

Two specific design methods are chosen in this design process:
Whole system mapping – it will be used to get a good overview of the whole product cycle and stakeholders involved. Secondly, it will be used to brainstorm ideas and see how they all can come together in the system. The map will be updated and detailed with each design iteration.
Biomimicry: Challenge to biology – the product context is the marine ecosystem, therefore, design challenges overlap with the challenges nature faces and has perfected its solutions for. Taking inspiration and learning from nature will also guide the design to align with natural ecosystems.

Meetings with the graduation committee and the company mentor will be planned every 3 weeks to present the progress and discuss the important parts for the project in that stage. Meetings with ARK Nature or their partners will be done on a weekly basis to present the design progress, discuss arising questions and design ideas.

Initials & Name J.M. Motuzaitė 5905 Student number 5393183

Title of Project Design for biodiversity: enhancing biogenic shellfish reefs

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.

Healthy and resilient ecosystems form the base for the health and wellbeing of the human population through crucial ecosystem services. With current trends of biodiversity loss and further weakening of ecosystems, there is no question that contemporary ways of Anthropocene pose major threats to wellbeing of the great majority of Earth's life forms. I believe that humans are not on the top of ecosystem but rather entangled within the system of complex networks and relationships. By acknowledging that, I want to act and use my skills to actively improve the ecosystem I am a part of as well as work towards solutions which could foster human-nature coexistence.

Acquired competences but want to further develop:

My previous experience includes a project which was aimed at tackling the wild pollinator decline problem in urban areas. From there, I already have acquired practical skills and base knowledge on how to approach design challenges in ecology field. While the pollinator project was aimed at urban areas and citizen education, I want to explore the other direction – designing solutions to help rewild natural areas on a larger scale, which could have more positive impact on the ecosystem.

During an elective course of Sustainable Design Strategies for Product Development, I got acquainted and practiced the Biomimicry method to develop a more sustainable product. A want to further develop my skills in using this method because it perfectly aligns with a nature-oriented design goal.

Competences I want to develop:

To further improve my skills and knowledge in design for biodiversity, how to create for non-human users and how to effectively communicate what ecosystem impacts the designed solution would have.

My previous designs for ecological challenges were based on a desk research about the species and their requirements. In this project I will be working with a team of marine biologists and ecologists. I want to learn how to effectively communicate and design the solutions alongside these experts of completely different field than mine.

Learn to effectively apply research through design approach to create effective solutions. Studying a challenge in the ecology field can easily overwhelm and slow down and even restrict creative thinking due to sheer amount of information intake. I want to strengthen my research through design approach to effectively iterate and gain knowledge in the most relative directions that the project and design direction asks. This also includes testing the design – how to use a wide array of tests to get the most effective feedback.

FINAL COMMENTS

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