Ôde à la Mer

Biorock as a building tool for future-proof architecture contributing to its ecosystem

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Table of Content

I. Project Definition **4-27**

Fascination 5

Biorock, a solution to embodied carbon reduction 6

Biorock, connecting architecture and ecology 8

Dutch context 10

The National park of the Oosterschelde 12

Research Questions 14

Design strategy 16

Experimentation as a design tool 18

Connecting architecture to another expertise 22

Design prospects 24

Theoretical framework 26

II. Research Results **28-55**

Material Research 30

Ecological Opportunities 36

Architectural Design Translation 40

III. Conclusion **58-75**

Biorock potential in the Dutch Context 60

Ecological Integration 64

Time as an architectural tool 66

LImitations 68

Reflection 70

Aknowledgements 72

Appendix 1: Biorock, Material technicalities **76**

Appendix 2: Material Growth Analysis **84**

Appendix 3: Design Experimentations **96**

Appendix 4: Location Analysis **110**

Appendix 5: Architectural Design **120**

I. Project Definition

Figure 1.01: *Experimental Biorock column. own picture, 4/6/26*

Fascination

Buildings are a fundamentally human response to environmental exposure, providing shelter from extreme temperatures, wind, rain, and unwanted natural intrusions. Through construction, humans create comfortable and controlled living environments. However, this raises an important question: what impact does this construction have on the natural environments in which it is embedded?

This question can be addressed across multiple scales, each revealing an imbalance between human benefit and environmental cost. On a global scale, climate change represents one of the most pressing environmental challenges, driven largely by carbon emissions resulting from human activity. While sectors such as transport and industry are often highlighted as primary contributors, the built environment is frequently overlooked. Yet it accounts for approximately 37% of global energy-related carbon emissions (Dyson et al., 2023)(figure 1.02).

On a local scale, the construction of buildings directly modifies ecosystems, reducing habitats for both flora and fauna. As urbanisation accelerates, many species gradually disappear from rapidly developing areas (Sobhani, 2024). Thus, from the scale of individual buildings to entire cities, the built environment enhances living conditions for humans while simultaneously diminishing natural qualities for other species.

This imbalance between human and non-human benefit raises the question of whether a new approach to architecture can be developed, viewing buildings as integral components of natural systems while reducing their negative environmental impact.

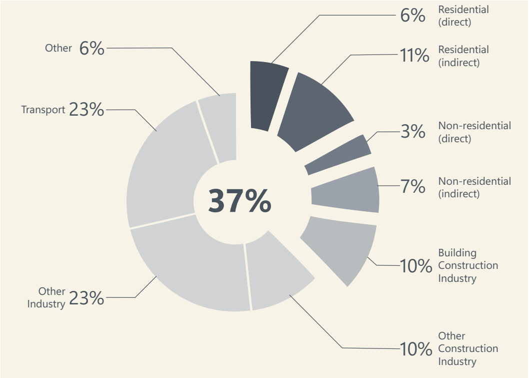


Figure 1.02: Global energy related carbon emissions from the construction sector (own diagram based on Dyson et al. 2023)

Biorock, a solution for Embodied Carbon Reduction

When developing architecture that is integrated into its surrounding ecosystem, its impact on both the immediate environment and global climate change should be minimised. In response to the significant contribution of the built environment to global carbon emissions, much research and many architectural projects have focused on reducing a building's operational carbon, the emissions associated with its use, such as heating, cooling, and lighting. However, strategies addressing embodied carbon, the emissions resulting from the production, transportation, and deployment of building materials remain comparatively limited (Sobhani, 2024).

A report by the United Nations Environment Programme and Yale CEA (2024) identifies three key strategies to reconcile building materials with climate objectives, one of which is a shift toward regenerative material practices through the use of ethically produced, low-carbon materials whenever possible.

Within this context, the development of alternative structural materials is particularly urgent, as the majority of contemporary construction relies heavily on concrete and steel.

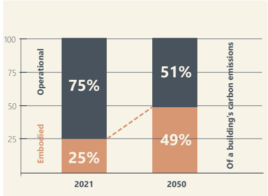


Figure 1.03:
Expected evolution of embodied and operational carbon emissions (own diagram based on UN Environment programme, n.d.)

Figure 1.04
Embodied and operational carbon emissions in the construction sector (own diagram based on UN Environment programme, n.d.)

This challenge brings attention to Biorock, a material conceived by architect Wolf Hilbertz in 1976, first called SeaCrete, his aim was primarily to develop modular building elements which could replace conventional materials such as concrete while requiring minimal raw materials and energy. Biorock is a mineral accretion formed through an electrolysis process in seawater (see Appendix for chemical reactions) (Goreau, 2012). Due to a lack of research on the subject and the inconvenience of its growth time, Hilbertz himself did not manage to practically use his material in an architectural context.

Biorock has not yet been applied in architectural construction and has instead found use primarily in marine ecology. However, recent research has increasingly focused on its technical and mechanical characteristics, like Johra's technical comparison of Biorock with concrete, or Margheritini's comparison with coral technical properties. Those are starting to identify its potential for future application within the built environment.

This raises the question of whether Biorock could contribute to a reduction of embodied carbon in architecture. Theoretical research on its material characteristics must therefore be translated into practical architectural applications in order to define its

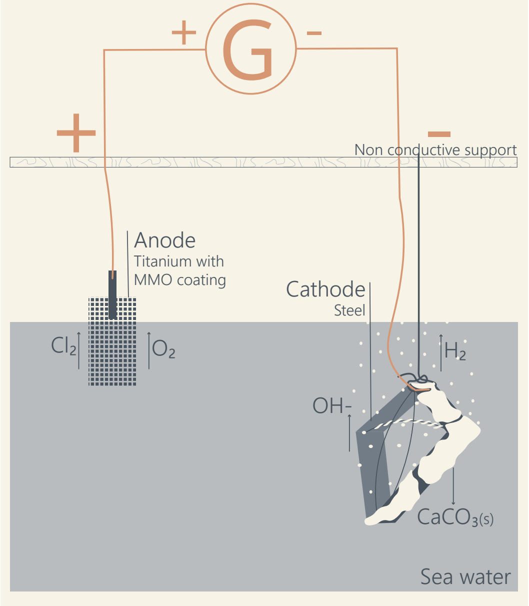


Figure 1.05
Biorock growth process diagram (own diagram)

Biorock, Connecting Architecture and Ecology

The material's primary use in the field of marine ecology results in a richer amount of data and research coming from that field. In 1987, architect Wolf Hilbertz was invited by biochemist Tom Goreau to explore the potential of Biorock technology for coral reef restoration. According to their research, the mineral accretion process not only produces a structural material but also significantly accelerates the growth of marine organisms, particularly corals (Global Coral Reef Alliance, 2019).

Following this collaboration, Hilbertz and Goreau founded the Global Coral Reef Alliance, an organisation dedicated to the research and development of Biorock technology for coral restoration in different tropical areas (BioRocks, 2024).

Figure 1.06
Biorock used to support coral reef growth
(Biorock Indonesia Is Restoring Coral With Electrified Reefs, 2021)

More recently, this line of research has expanded beyond tropical regions to Europe. Research in Denmark and the Netherlands are looking into the effect of mineral accretion on marine species like fouling communities or mussels. Experiments have started in September 2025 in a port of Texel that seeks to enhance growth rates of mussels. Mineral accretion thus presents potential as a method for enhancing marine ecosystems that are currently under pressure from human activity and climate change.

If architecture is understood as an active component of natural ecosystems, capable of contributing to ecological processes rather than displacing them, then materials such as Biorock invite new architectural possibilities. Building materials could then start to be thought of not only as protection for our comfort, but also as hosts for many other forms of life, enhancing biodiversity rather than diminishing it.

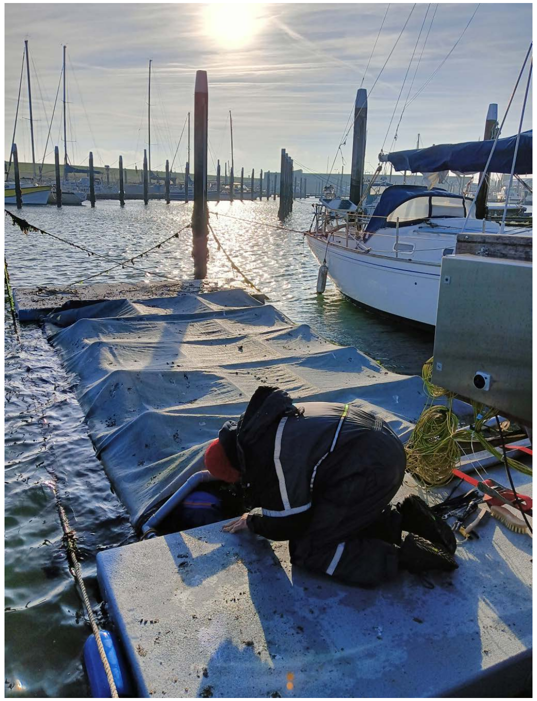


Figure 1.07
Research experiment location in Texel (Own picture, dec 2025)

Dutch Context

The Netherlands presents a peculiar case in its relationship with the natural environment. Beyond seeking protection within buildings, Dutch society has historically developed strategies to protect its built environment from natural forces. As a low-lying country, with large areas situated below sea level, the Netherlands has long engaged in the management and control of its landscape through engineered ecosystems.

While these techniques have proven highly effective, the accelerating consequences of climate change pose increasing challenges to their continued viability. Projected sea-level rise, estimated between 2 and 5 metres, places significant pressure on existing flood protection systems (Utrecht University, 2022).

This context allows the broader question raised earlier to be reframed within the Dutch condition: rather than designing architecture that is protected from nature, could the built environment be conceived as an integral part of natural ecosystem? Such an approach would suggest a shift from defensive infrastructural strategies towards architectural systems that engage with, adapt to, and potentially support surrounding ecosystems. This design aims to provoke the conventional way to design architecture to open the way to an architecture codeveloping with its ecosystem and for its future.

Figure 1.08
(Nationaal Park Oosterschelde | Op Schouwen-Duiveland, n.d.)

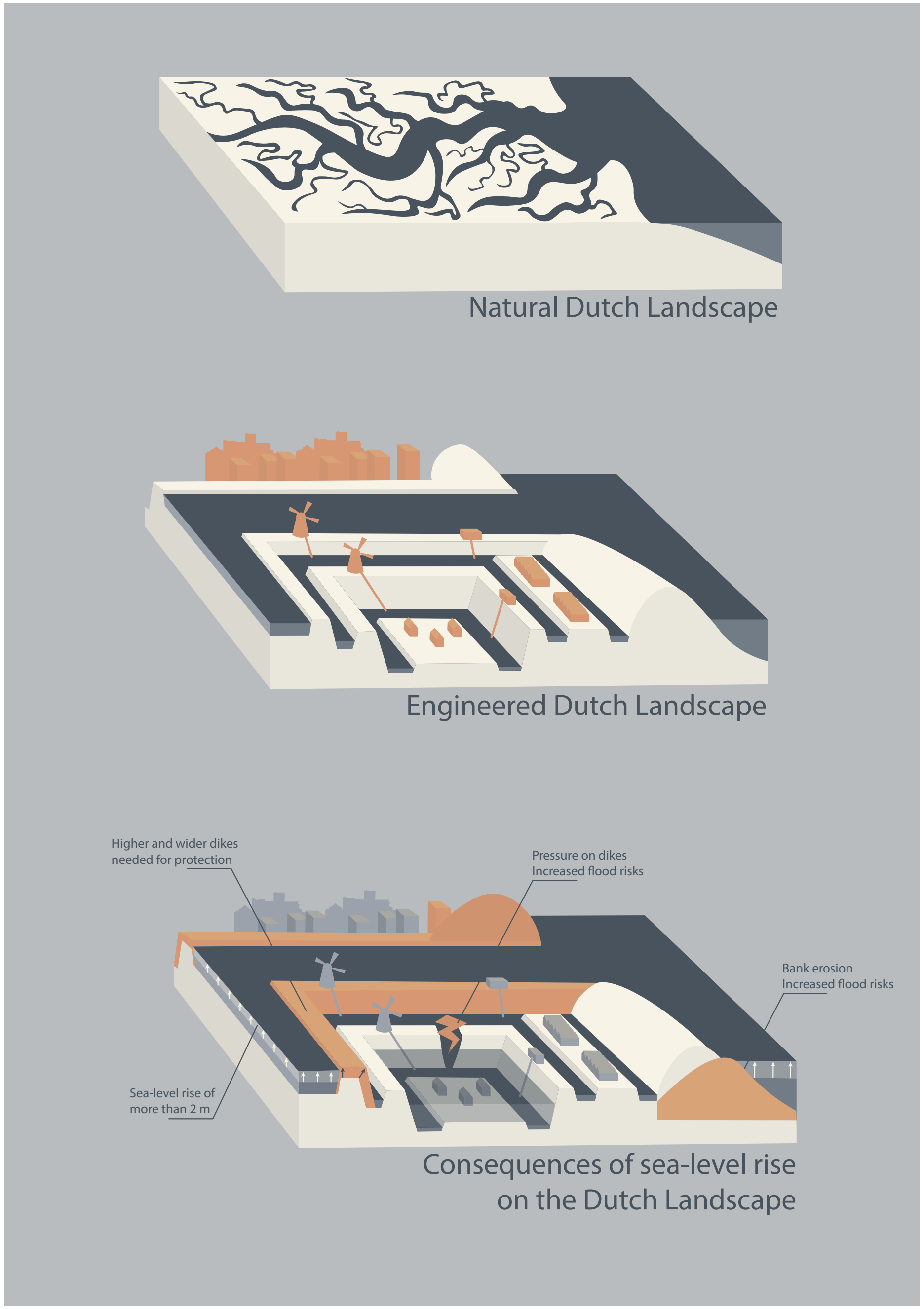


Figure 1.09
Past, present and future of the Dutch Landscape (own diagram)

The National Park of Oosterschelde

Within this context, the Oosterschelde National Park offers a critical site for exploring alternative relationships between architecture and marine ecosystems. As a tidal estuary with high salinity and significant ecological value, it is both intensively studied and increasingly vulnerable to climate-driven challenges. These conditions make the Oosterschelde a suitable testing ground for architectural interventions that move beyond protection and instead engage with natural processes.

▨ Partially open dam
▬ Closed dam
35 ppt ↑ 0 ppt Water salinity
▪ Existing buildings

🟧 Partially dry
■ -44 m
■ -35 m
■ -25 m
■ -15 m
■ -5 m
▪ Existing buildings

This thesis therefore investigates how an architectural project in the Oosterschelde, using Biorock as a one of its main building materials, can function as an educational and ecological interface, proposing a model in which architecture contributes to both human understanding and marine ecosystem regeneration.

Salinity map of Zeeland

Figure 1.10 (own diagram)

Water depth map Oosterschelde

Figure 1.11 (own diagram)

Research Questions

How can Biorock technology be translated into an architectural design tool to reduce embodied carbon while integrating it as part of the natural ecosystem of the Oosterschelde?

This main question is divided into two research themes:

Part I:
First, the project focuses on the practical application of mineral accretion in the construction, leading to the following sub-questions:

Could Biorock be used to reduce the embodied carbon in the construction of a building?

In which construction layer could Biorock be applied most effectively?

How can architectural details be designed to connect Biorock elements to the other layers of the building?

Part II:
In addition to its practical and technical applications of the material's its more widely known use in marine ecology has the potential to inform the development of an architecture integrated in its ecosystem. Using Biorock as a design tool for buildings that contribute to their ecological environment is therefore the second theme, which is divided into the following sub-questions:

In the Dutch context, how can architecture be designed to be part of its natural ecosystem rather than being protected from it?

Which species and ecological issues could most benefit from a structure designed using mineral accretion?

How can the life cycle of a building be designed in a changing and unprotected landscape?

In what ways can the design of a building help to reconnect people with the marine ecosystem and raise awareness of the challenges it faces?

Design Strategy

This project adopts a research-by-design methodology, combining material experimentation, ecological research, and architectural design. The aim is to design a marine educational and research centre in the Oosterschelde that responds simultaneously to human needs and the ecological requirements of its marine environment, using Biorock as one of the primary building materials.

The site location is determined through an analysis of the Oosterschelde, identifying areas that both provide favourable conditions for Biorock growth and exhibit significant ecological value or challenges (see location analysis Appendix 3). The design process is therefore informed by two interconnected research trajectories. The first focuses on Biorock, investigating its growth process and practical potential as an architectural material. The second examines marine ecology, specifically within the Oosterschelde, its current conditions, challenges, and opportunities for architectural intervention. These trajectories overlap where Biorock functions as a material capable of supporting marine life.

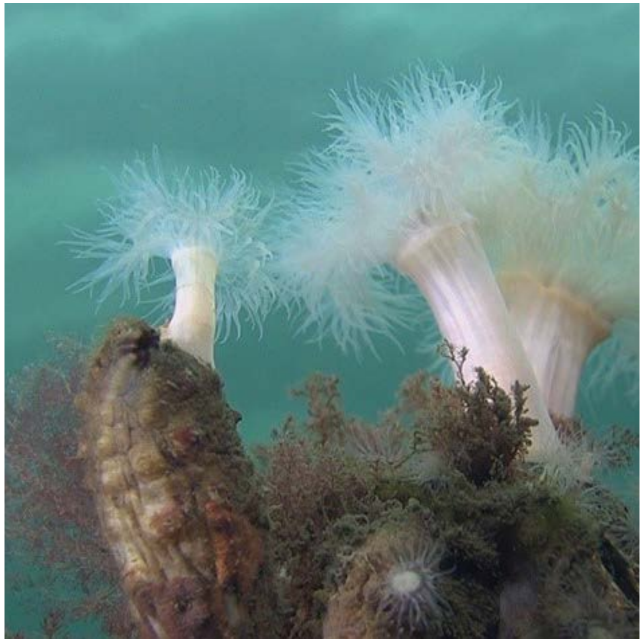


Figure 1.12
Rijk Onderwaterleven in De Oosterschelde - Natura 2000
Rijkswaterstaat, n.d.

Figure 1.13
First result material from 2 weeks of aquarium-based growth experiment (own picture)

Experimentation as a design tool

Experimentations in aquarium

Existing research on Biorock has largely focused on its technical and mechanical characteristics (Johra, et al, 2021). This project builds upon those findings and seeks to translate theoretical knowledge into practical architectural applications. Material experimentation forms the primary research method, with a focus on modularity, constructability, and life cycle considerations.

Initial design hypotheses for modular Biorock elements are developed through sketches informed by existing literature (sketches Appendix 2). These elements are then tested through scaled-down growth experiments conducted in two environments: a controlled aquarium setting and an open marine context. This dual approach, comparing results obtained under controlled conditions and real-world marine environments, allows to assess the potential and limitations of Biorock as a building material.

Aquarium experimentation set-up

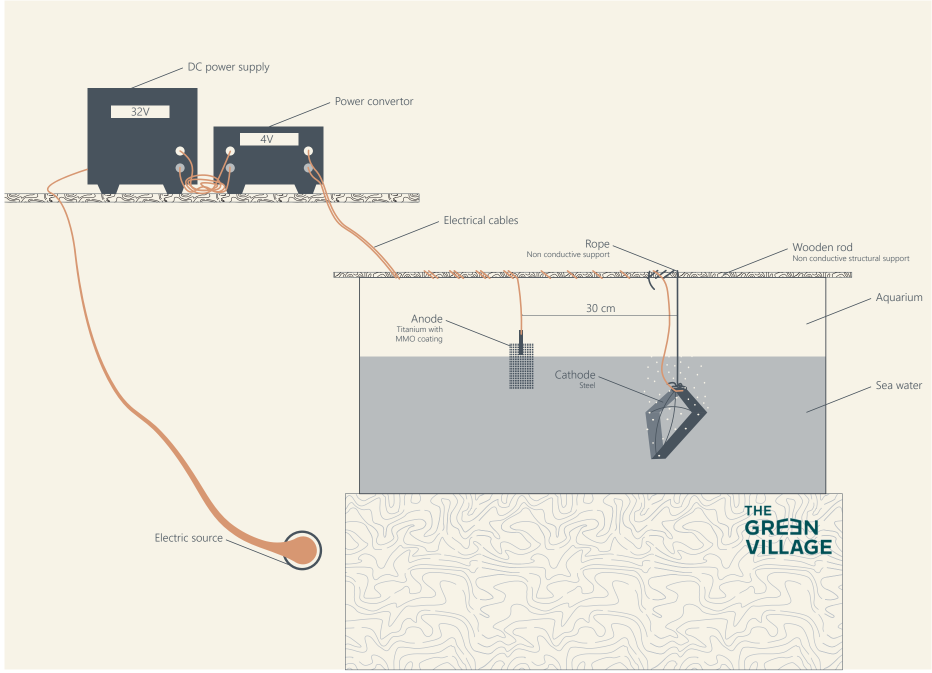
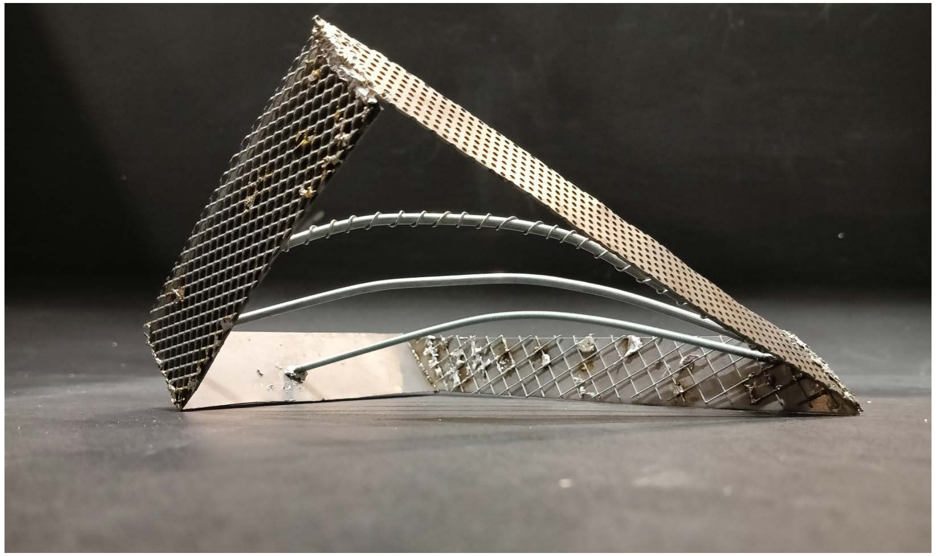


Figure 1.14 (Own diagram)



Cathode for first experiment testing the growth on several surfaces (Own picture)

Figure 1.15
Biorock on steel cathode after one week of growth (Own picture)

Experimentation as a design tool

Experimentations in sea environement

In parallel to the controlled aquarium experiments, the project engages with ongoing marine ecology research conducted by Wageningen University. Through collaboration with researchers investigating the effects of mineral accretion on mussel and fouling communities (Coolen, 2025), the project gains access to an experimental setup in the port of Texel.

Within this framework, up to three Biorock experiments can be placed within existing infrastructure that provides electrical connections. These experiments are monitored less frequently, approximately once per month, but allow for direct comparison between aquarium-grown and sea-grown Biorock. Growth periods are expected to last approximately 2 months, providing insights into material behaviour under real marine conditions relevant to the project site.

Together, the aquarium and sea experiments inform conclusions regarding Biorock's effectiveness as a building material and will form the base for the building design.

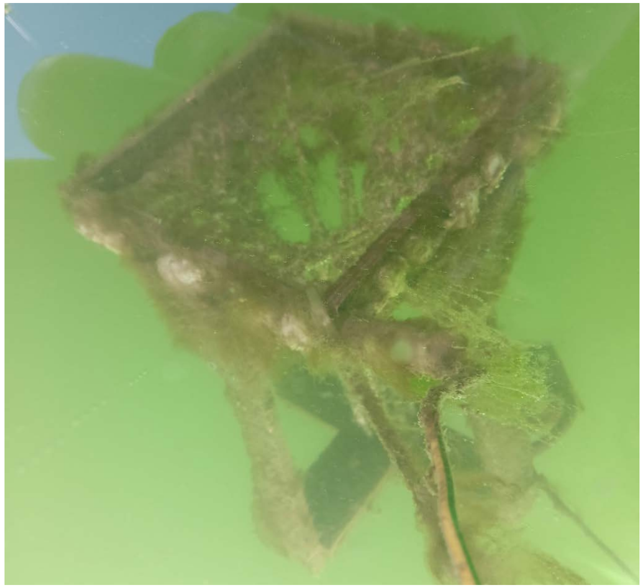


Figure 1.16
Mineral accretion on mussel cage (Own picture, 4/12/2025)

Figure 1.17
Experiment observation in the sea
(Own picture, 4/12/2025)

Connecting Architecture to other Expertise

Inspired by the design approach of architectural practice Ro&Ad, the project integrates ecological expertise directly into the design process. Collaboration with marine ecologists supports an in-depth understanding of the Oosterschelde's ecosystem, its strengths, and its current challenges.

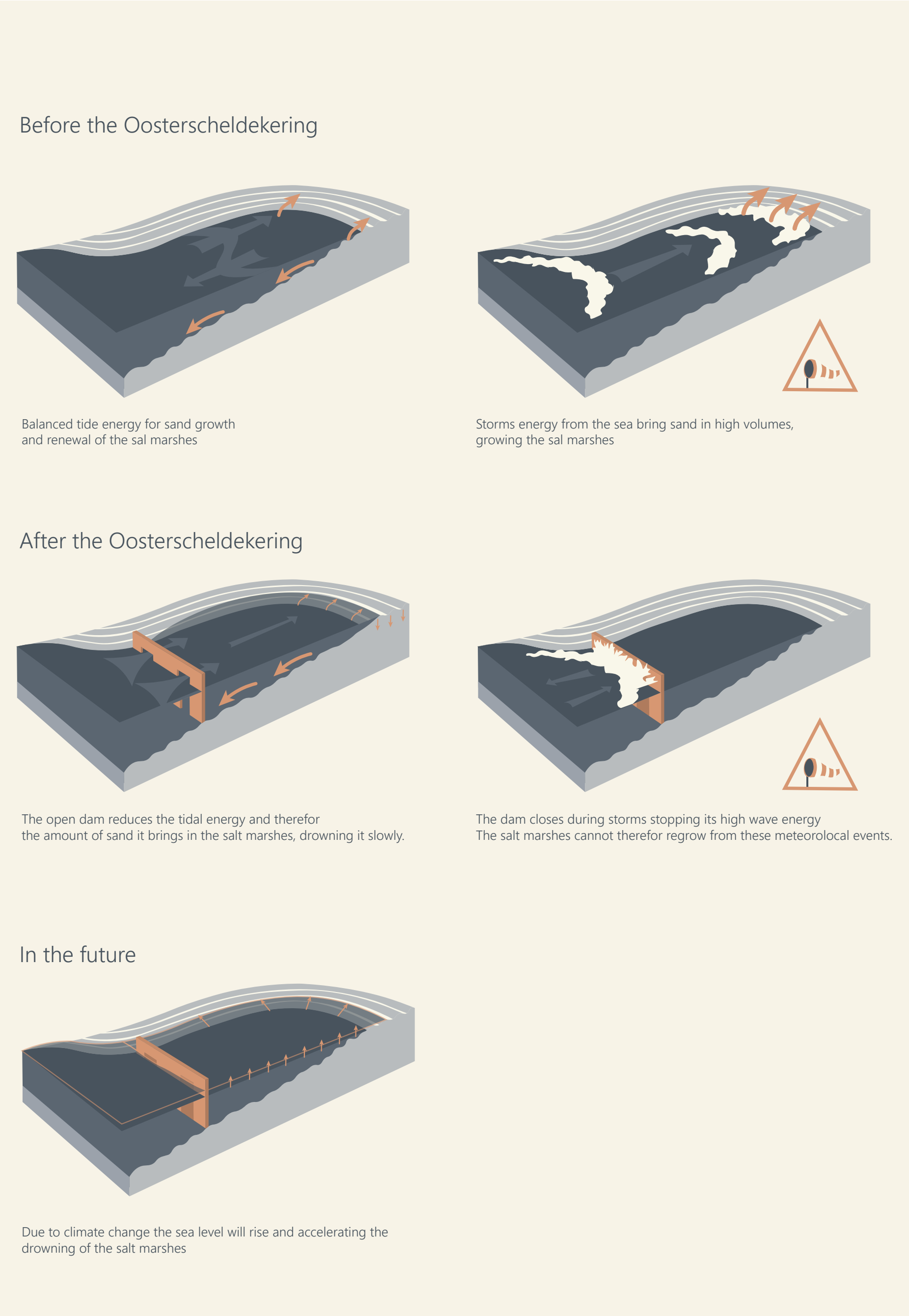
This knowledge is gathered through literature review and expert interviews. Key contributors include Wageningen University researchers Joop Coolen and Enzo Kingma, focusing on the effect of mineral accretion on marine species, and marine ecologist Jim van Belzen (NIOZ), specialist of ecology challenges of the Oosterschelde like sand starvation, its causes, consequences and results of research on possible solutions.

Insights from academic research, expert discussions, and material experiments are synthesised into architectural design principles guiding the development of the educational centre.

Figure 1.18
Van Belzen et al., 2025

Studying the effect of nature inspired spatial design on bank erosion in the Oosterschelde

Sand starvation problematic of the Oosterschelde explained



Before the Oosterscheldekering

Balanced tide energy for sand growth and renewal of the sal marshes

Storms energy from the sea bring sand in high volumes, growing the sal marshes

After the Oosterscheldekering

The open dam reduces the tidal energy and therefor the amount of sand it brings in the salt marshes, drowning it slowly.

The dam closes during storms stopping its high wave energy The salt marshes cannot therefor regrow from these meteorolocal events.

In the future

Due to climate change the sea level will rise and accelerating the drowning of the salt marshes

Figure 1.19: own diagram

Design Prospects

The ecological challenges facing the Oosterschelde operate at a scale that cannot be resolved through a single architectural intervention. Instead, this project aims to design a building that raises awareness while demonstrating the potential of an alternative architectural approach, one that reconciles human comfort with ecological integration rather than environmental separation. This will be achieved through the design of an educational centre as an extension of the existing Watersnoodmuseum in the northern part of the Oosterschelde.

The current museum focuses on the history and engineering of the area; an additional programme raising awareness of its marine ecology could connect the public to the research conducted by NIOZ and Wageningen University in the Oosterschelde, while also providing the renewed appeal the museum is currently seeking. Moreover, the museum is located adjacent to a tidal low marsh, the Slikken van Viane, which represents both a rich and ecologically challenging area.

The proposed marine educational centre, inspired by comparable institutions around the Wadden Sea, focuses on both the ecological richness and the vulnerabilities of the Oosterschelde. The building will also include research spaces focusing on Biorock to further develop its potential ecological and architectural use. The programme will be designed in a maximum indoor surface of 600m² on two levels, including on the one hand public functions for educational purpose and private functions for research purposes:

Educational center:
- Reception, 80m²
- Two Exhibition spaces
    - Indoor flexible exhibition space, 150m²
    - Marine ecological viewing area, 140m²
- Small cinema/conference room, 30m²
- Garderobe and Toilets, 30m²
- Staffroom, 15m²
- Depot, 25m²
- Technique, 20m²

Research center:
- Indoor lab, 30m²
- Offices, 50m²
- Cantine, 20m²
- Toilets, 10m²
- Outdoor lab structure

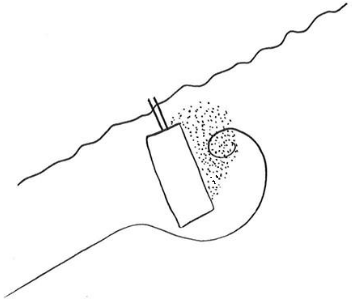


Figure 1.20: Design by anticipating its impact on the environment and use it to become part of it (own drawing)

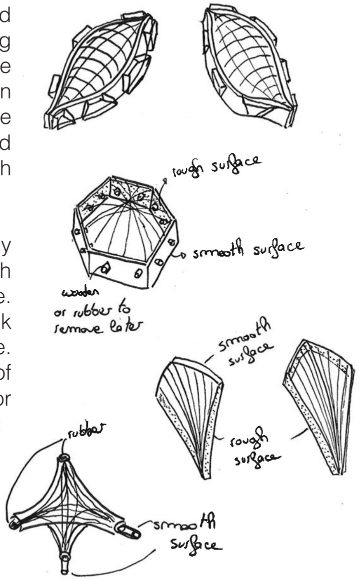


Figure 1.21
Modular element design sketches (own drawing)

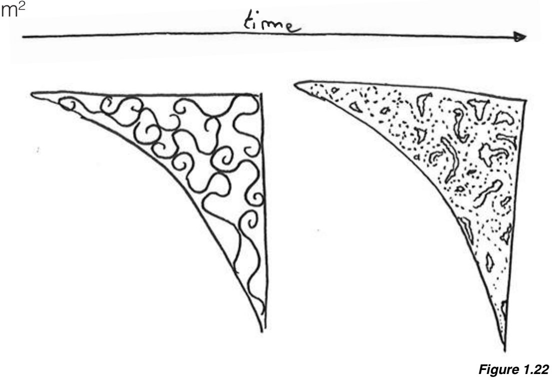


Figure 1.22
Design decorative details with natural growth (own drawing)

Outdoor spaces:
- Roof terrace, 150m²
- Ecological roof, 150m²
- Bench areas, 50m²
- Deck access to research center

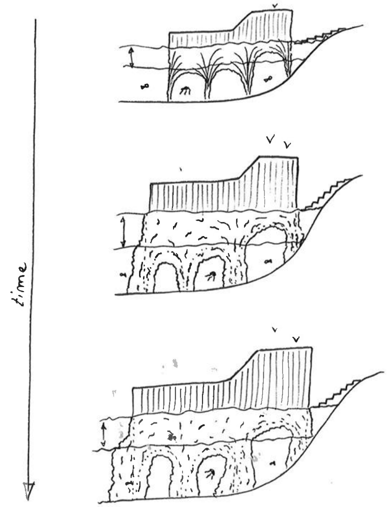


Figure 1.23
A building evolving through time depending on the tides (own drawing)

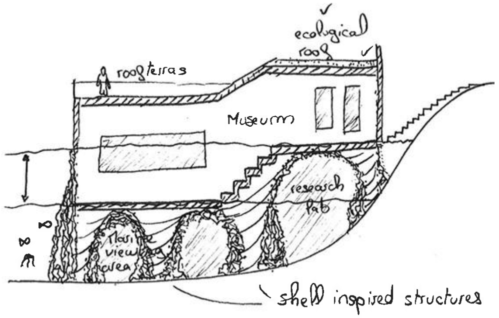


Figure 1.24
A building as an observation point of a changing landscape (own drawing)

Figure 1.25
Watersnoodmuseum, n.d.

Theoretical framework

The theoretical framework supporting the design research consists of two main bodies of knowledge: research on Biorock and research on the Oosterschelde's marine ecosystem.

Biorock: growth and material characteristics

The research focused on Biorock is somewhat limited even though it developed in recent years. Foundational research by Wolf Hilbertz and Tom Goreau forms the basis of understanding Biorock technology, particularly its growth mechanisms and ecological effects (Goreau, 2012). More recent studies have expanded this knowledge to include material testing and comparisons with conventional construction materials such as concrete (Johra et al., 2021). On the architectural part, studies on Biorock, like the master thesis of Camron Penney (2023), open the way to practical applications of the material. This literature provides the theoretical grounding for translating Biorock into architectural applications.

Marine ecosystem: strengths and challenges

The Oosterschelde is extensively studied due to its ecological significance. Literature addressing long-term ecological development and biodiversity, including work by Ysebaert (2013) and Troost et al. (2012), is used to identify current challenges within the ecosystem. This is complemented by contemporary research exploring adaptive, nature-based solutions, such as Jim van Belzen's work on erosion mitigation (2025).

Finally, literature that bridges material and ecological research, such as studies on mineral accretion in marine environments (Coolen, 2025) and Aalborg University's research on sustainable reuse of offshore infrastructure (2020), supports the integration of Biorock within ecological architectural design.

II. Research Results

Figure 2.01: *(Own picture, 2026)*

Since the project aims to explore the practical application of new material for the building sector, the study of this material is an integral part of it. The results are, similarly to the research topics, divided in two directions, with the material study as the foundation of the project, completed by the ecological investigation of the Oosterschelde. The knowledge gained through these two studies informs the architectural design objective and parameters. The results of each study are explained separately before bringing those together through the architectural design.

Material Research

Biorock is a material currently used in marine ecology. This section presents the results of a preliminary study of its potential for application in the architecture in order to reduce the embodied carbon of a building. The results first discuss the growth of the material itself where the potential practical applications results build upon. The chapter ends with assumptions made based on the obtained results, required for the architectural design following.

a. Growth Experiments

Biorock growth was investigated through experiments conducted in both a controlled aquarium environment and in open sea conditions. The aquarium experiments allowed observation of how environmental parameters influence the growth process, while the open sea experiments provided insight into the material's behaviour under realistic marine conditions.

The aquarium experiments indicated that water temperature between 11 °C and 15 °C does not significantly limit the growth process, suggesting that Biorock formation is possible in the colder conditions of the North Sea. Among the measured parameters, pH showed the strongest influence on growth. A decrease in pH caused by corrosion of a steel anode significantly reduced material formation, while stable conditions between approximately pH 7 and 9 resulted in more effective calcium carbonate deposition. The experiments also demonstrated that the chemical growth process itself gradually lowers the pH in closed water systems, highlighting the importance of maintaining stable water conditions. Variations in salinity, measured through specific gravity, did not show a clear influence on growth within the tested range.

The open sea experiments provided conditions closer to the intended application environment, with relatively stable pH, salinity, and electrical parameters. Material grown in these conditions showed differences compared to the aquarium samples, including variations in colour that may be related to nutrients present in seawater. Early stages of biological colonisation, such as algae growth, were also observed on the material surface.

Overall, the experiments indicate that Biorock growth can occur under North Sea conditions and that stable chemical parameters, particularly pH, are important for effective material formation. Open sea environments may therefore provide favourable conditions for producing the material in practice.

For detailed growth analysis see Appendix 2.

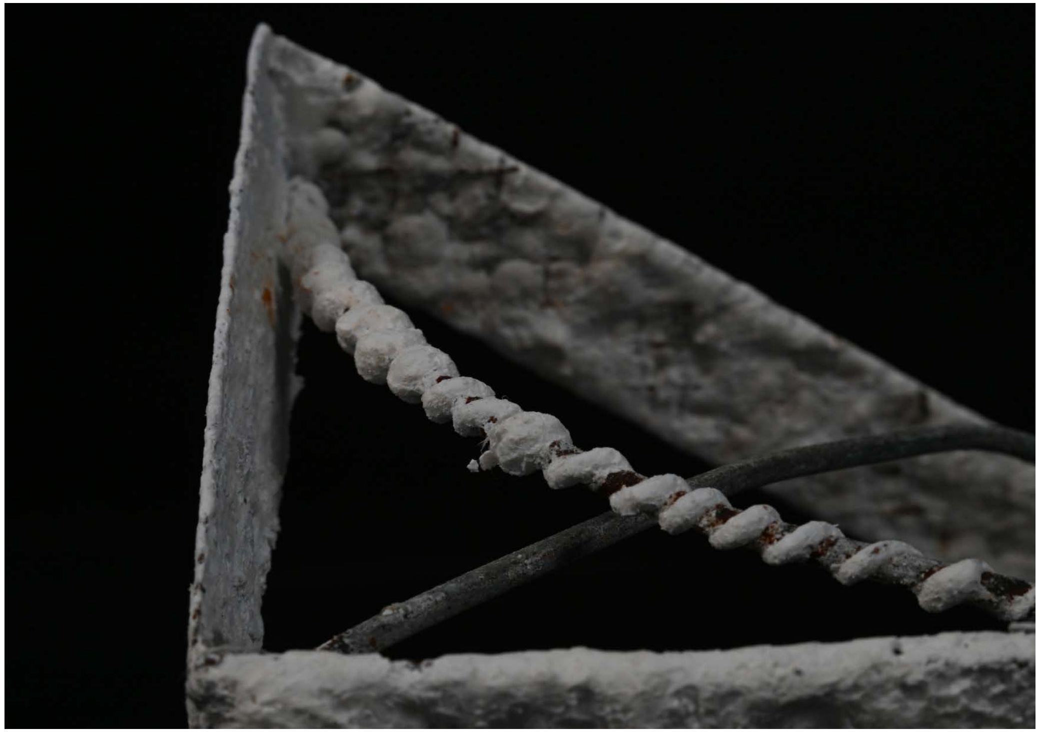


Figure 2.03: Own picture, 2026

b. Design experiments

In addition to studying the growth conditions of Biorock, a series of design experiments was conducted to explore how the material could be applied in an architectural context. These experiments investigated how different structural configurations influence the growth behaviour of the material and how Biorock could be integrated into lightweight construction systems.

A first set of experiments focused on the influence of surface characteristics on material growth. Smooth steel surfaces resulted in thin layers of Biorock that detached easily, while rough or entangled steel wires showed significantly stronger and faster accumulation of material. These observations suggest that surface roughness and structural complexity improve the adhesion and stability of the mineralised layer.

Further experiments explored how lightweight structures could be shaped before the Biorock growth process. Organic structures, such as branches (figure 2.04) or shell-inspired geometries (figure 2.05), were used as temporary supports or structural guides for the steel framework. While these experiments demonstrated that Biorock can successfully mineralise irregular and organic forms, the resulting material properties varied depending on growth conditions such as electrical current and environmental stability.

Additional structural experiments tested the potential of Biorock to connect and strengthen lightweight steel frameworks (figure 2.06). Observations indicated that material growth was particularly strong at connection points and areas where multiple wires intersected. This suggests that Biorock can effectively mineralise and stabilise joints between structural elements.

Finally, a wall-detail experiment explored the possibility of combining steel reinforcement with fabric and moulds to guide the growth of the material into controlled shapes (figure 2.07). The results showed that Biorock can grow through porous materials such as fabric, creating a cohesive mineralised layer that connects different components of the structure.

Overall, the design experiments indicate that Biorock is most effectively used as a mineralised structural system growing around a lightweight framework rather than as a solid material volume. Structural efficiency can be improved by increasing surface roughness, using intersecting structural elements, and guiding the growth of the material through lightweight moulds or supporting materials.

For detailed research results per design experiment see Appendix 3.

Figure 2.04
Starting and final structure after 2 weerks of growth in aquarium (Own pictures, 2026)

Figure 2.05
Starting and final structure after 4 months of growth in marine environment (Own pictures, 2026)

Figure 2.06
Starting and final structure after 4 months of growth in Marine environment (Own pictures, 2026)

Figure 2.07
Starting and final structure after 3 weeks of growth in aquarium (Own pictures, 2026)

c. Assumptions for Architectural Application

The use of Biorock as a building material is a relatively new concept, although the idea has existed for several decades. Due to the limited amount of existing research, many hypotheses have been formulated regarding its material properties and potential practical applications. In recent years, an increasing number of studies have begun to test these hypotheses. However, the available results remain limited, and small-scale, short-term experiments cannot verify all assumptions about the material. For this reason, several assumptions must be made in order to enable the architectural design developed in this project.

In recent years, research has increasingly focused on the material properties of Biorock, such as the work of Johra et al. (2021). In this study, Biorock samples were tested to determine a range of material characteristics, including mechanical strength and thermal properties. The results showed similarities with Portland concrete of class C20/25, which is commonly used for low-rise constructions. Based on these similarities, this project assumes that for technical properties of Biorock that have not yet been measured, the corresponding values of Portland concrete can be used as a reference.

Observations from small-scale samples also suggest that, similar to concrete, Biorock performs well in compression but is relatively weak in tension. This assumption influences the structural design strategy, which therefore focuses on the efficient use of compressive forces.

Johra’s research further compared Biorock samples grown under different voltage conditions, distinguishing between low- and high-voltage growth. These experiments confirmed that variations in electrical conditions affect the mineral composition of the material, particularly the ratio between aragonite and brucite. Low-voltage growth promotes aragonite crystallisation, resulting in stronger material properties, while high-voltage growth promotes brucite formation, which leads to more brittle samples.

In addition to these differences, observations of retrieved samples revealed variations between wet and dry material conditions. Wet samples appeared to dissolve relatively easily when handled and required thicker material layers to achieve the desired strength. In contrast, dry samples showed significantly higher compressive strength. For the purpose of this project, it is therefore assumed that structural elements made from Biorock are most efficiently used in dry conditions.

While the mechanical properties of Biorock may be comparable to those of concrete, the growth process represents a fundamental difference between the two materials. Concrete is typically designed and applied as a solid material volume, whereas Biorock forms through mineral deposition around a lightweight framework. For reasons of material efficiency, Biorock is therefore best understood and designed as a mineralised structural system rather than as a massive construction material.

Figure 2.08: *Own picture, 2026*

Ecological Design Opportunities

This project explores the use of Biorock as a building material to create comfortable spaces for human visitors while simultaneously benefiting the ecological environment in which the building is located. Within this project, two ecological contexts can be distinguished: the environment above water and the marine environment below water. As the building interacts with both, each can be integrated into the design in different ways.

a. Coastal ecosystem

An example of architectural design benefiting both humans and the surrounding ecosystem is the Veldstation Saeftinghe in Zeeland, designed by Ro&Ad. In this project, indoor spaces are designed for human use and comfort, while the building envelope supports ecological functions. The attic spaces are kept open and space beneath the building provides shelter for birds, bats, and other animals. The façade contains elements filled with organic materials such as sand, sedum, wood, stone, or shells, creating habitats for insects, bats, and small birds (Kil & Koster, 2023). The gently sloped roof also provides safe nesting areas protected from predators such as foxes and rats (Kil & Koster, 2023).

Predation is one of the main causes of reproduction failure of oystercatchers in the Oosterschelde (M. Frauendorf, 2022). This bird species plays an important ecological role in the area, but its population has declined significantly in recent decades (figure …). Research suggests that reproduction could be improved through the creation of safe breeding areas and the presence of grasslands near the coast, which have shown beneficial effects on the birds' body condition (M. Frauendorf, 2022).

Figure 2.09
Farnsworth, 2024

b. Marine ecosystem

Design strategies that benefit ecological systems can also be applied to marine environments. In recent decades, several projects have explored marine-oriented design, such as the 3D-printed marine habitat developed by Zaha Hadid Architects. This project incorporates engineered shapes and textures that encourage the settlement of algae, filter-feeding shellfish, and other foundational organisms, forming a food chain that supports higher levels of marine life (Torres, 2025).

Although this structure was designed entirely to support marine life, similar principles could be applied to the outer shell of a building partially or fully constructed underwater. Inspiration for this approach can be found in biodiversity enhancement strategies used in offshore wind farms in the North Sea (Bureau Waardenburg, 2020).

Artificial reef structures can support marine biodiversity by providing shelter and substrate for marine organisms. Historically, reefs in the North Sea were largely formed by shell beds dominated by flat oysters. These reefs created biodiversity hotspots that supported species such as crabs, bryozoans, fish, hydrozoans, starfish, sponges, and thornback rays (Bureau Waardenburg, 2020).

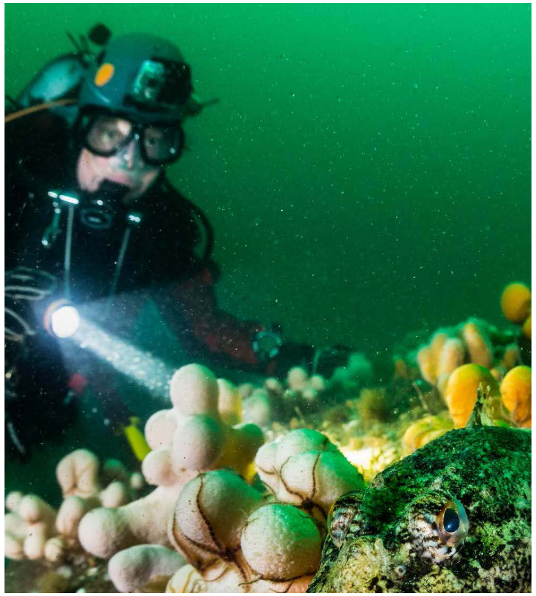


Figure 2.10
Bureau Waardenburg, 2020)

Flat oysters are common in the Oosterschelde, which is also an important region for oyster farming. Integrating oysters into the building design could therefore be an initial step toward supporting the surrounding ecosystem. Another important reef-forming species is the blue mussel, known for creating extensive reefs in intertidal zones (Bureau Waardenburg, 2020). These reefs occur at shallow depths between 1 and 10 meters and provide food and habitat for fish, crabs, and birds. Blue mussels can also coexist with flat oysters, which helps reduce predation by starfish (Bureau Waardenburg, 2020).

Biorock forms a hard substrate that has shown beneficial effects on the development of shell-forming organisms such as mussels and oysters (Van der Henst, 2021). Combining this substrate with shell-forming species could attract reef-associated organisms such as cold-water corals and anemones, which in turn create habitat for additional species (Bureau Waardenburg, 2020). Such reef structures can then attract larger mobile species seeking food and shelter, ultimately supporting the development of a complex marine ecosystem.

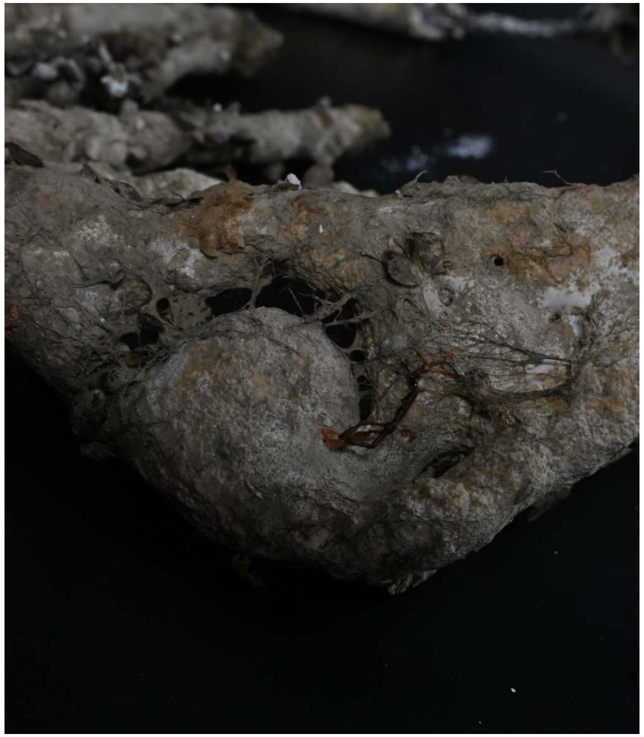


Figure 2.11
Sea life observation on dried experiment result (own picture)

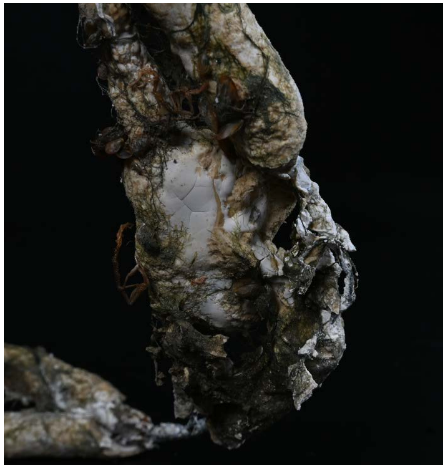


Figure 2.12
Sea life observation on dried experiment result (own picture)

Architectural translation

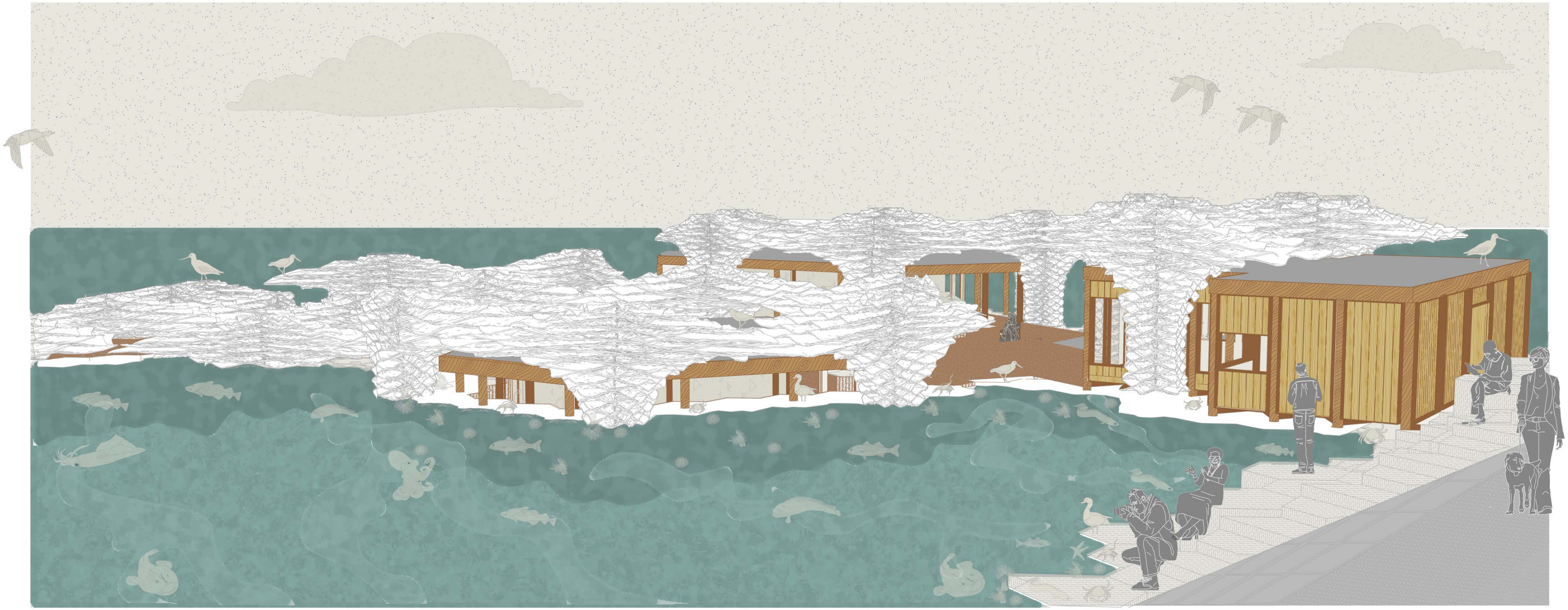


Figure 2.13
High tide impression

The design of this project aims to achieve three main goals. The first is to explore the practical use of Biorock as a building material. The second is to combine the design with the material in order to create a building that is beneficial to both humans and the surrounding ecosystems. The final goal is to develop a design that enhances the visitor's experience of the ecosystem of the Oosterschelde.

The design draws attention to the different components of this complex ecosystem by remaining open to it, attracting it, and supporting it. To enhance this experience, the building is conceived as a gradient that transitions from a human-centred design to an ecologically centred one. Humans therefore enter a welcoming building and gradually move toward spaces where they become visitors within the habitats of other species.

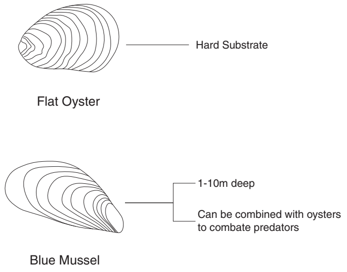


Figure 2.14

Reef building species

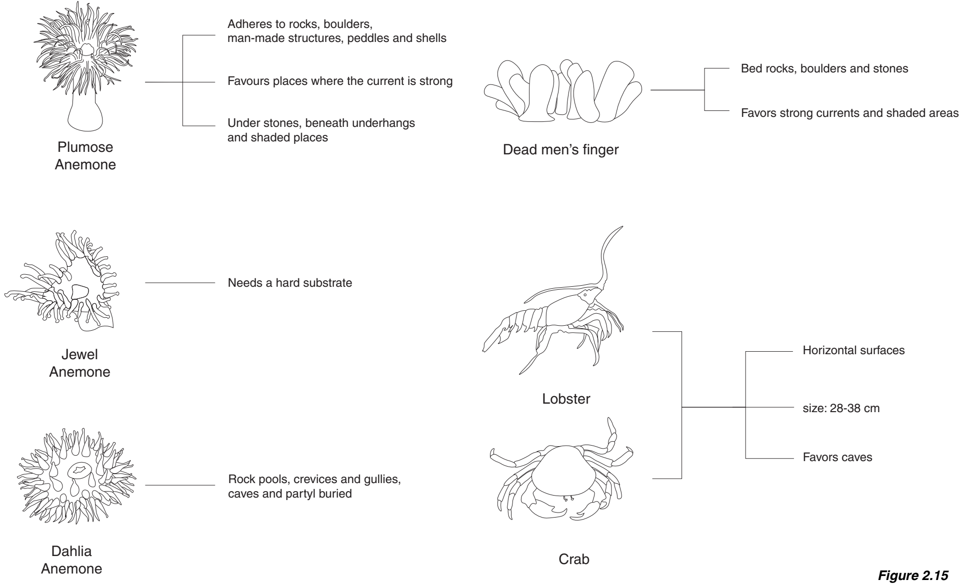


Figure 2.15

Reef associated Species

Until the end of the nineteenth century, natural reefs occupied significant areas of the Dutch North Sea, providing habitats for complex marine ecosystems. Due to intensive bottom trawling, these reefs largely disappeared, significantly reducing the biodiversity of the largest natural area in the Netherlands (Bureau Waardenburg, 2020). In response, the project proposes architecture conceived as an inhabitable reef structure within which both marine ecosystems and visitors can coexist.

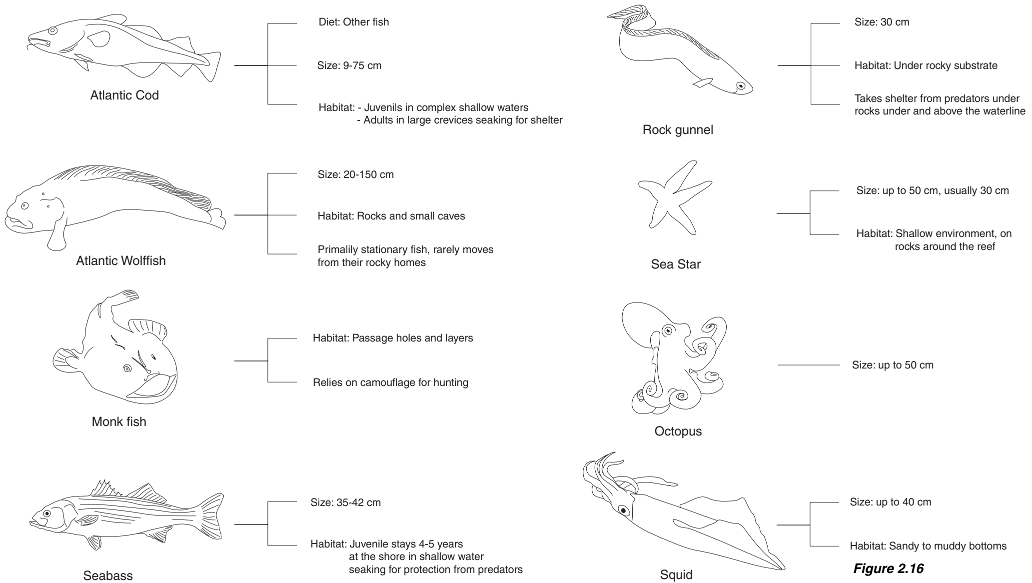


Figure 2.16

Reef benefitting species

The reef is designed as a modular system in which Biorock forms the hard substrate upon which reef-building and reef-associated species can develop and attract additional marine life (see figure ... module diagram). The module is specifically shaped to accommodate different species by incorporating cavities and sheltered spaces of varying sizes suitable for juvenile and small fish species. The horizontal layers additionally create habitats for crabs and lobsters while forming shaded areas and small tidal pools during low tide.

The reef module consists of layered steel mesh structures onto which Biorock is grown. In permanently submerged or deeper areas, the material would ideally be grown directly at its final location. In shallower conditions, elements could be partially grown elsewhere before being relocated to continue a slower mineral accretion process on site (see figure 2.26).

The modules are stacked into clustered formations that support different ecological conditions for different species. The dense central zones primarily provide protected habitats for juvenile fish species, while the outer layers offer shelter and feeding opportunities for medium-sized fish, octopuses, and starfish exposed to stronger water currents. The passages between the reef clusters create circulation zones for larger predator species such as Atlantic cod and seabass (see figure 2.18).

A second module applies the same principles through a vertical column-like structure. These columns are positioned both below and above the water surface (see figure 2.17). Underwater, they contribute to marine habitats similarly to the reef modules, while above water they create opportunities for insects and birds, including nesting habitats. Simultaneously, these vertical structures contribute to the spatial atmosphere and visitor experience of the architectural complex.

Through time, the gradual growth of the Biorock structures and the increasing biodiversity of the reef transform the project into a layered ecosystem both above and below water, forming the ecological foundation upon which the human experience is organized.

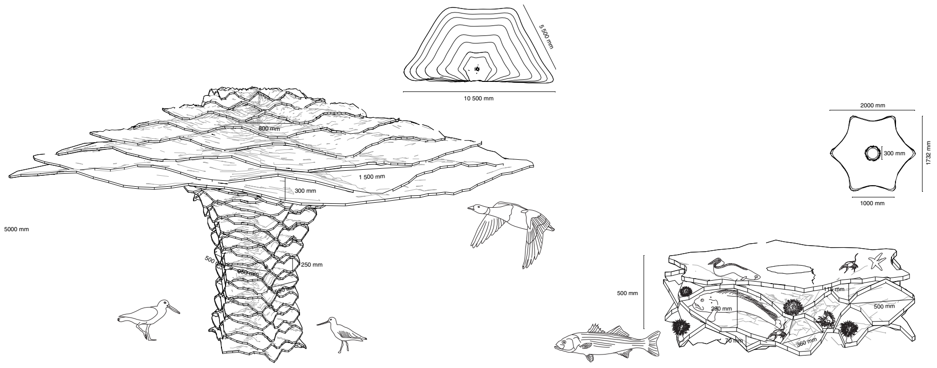
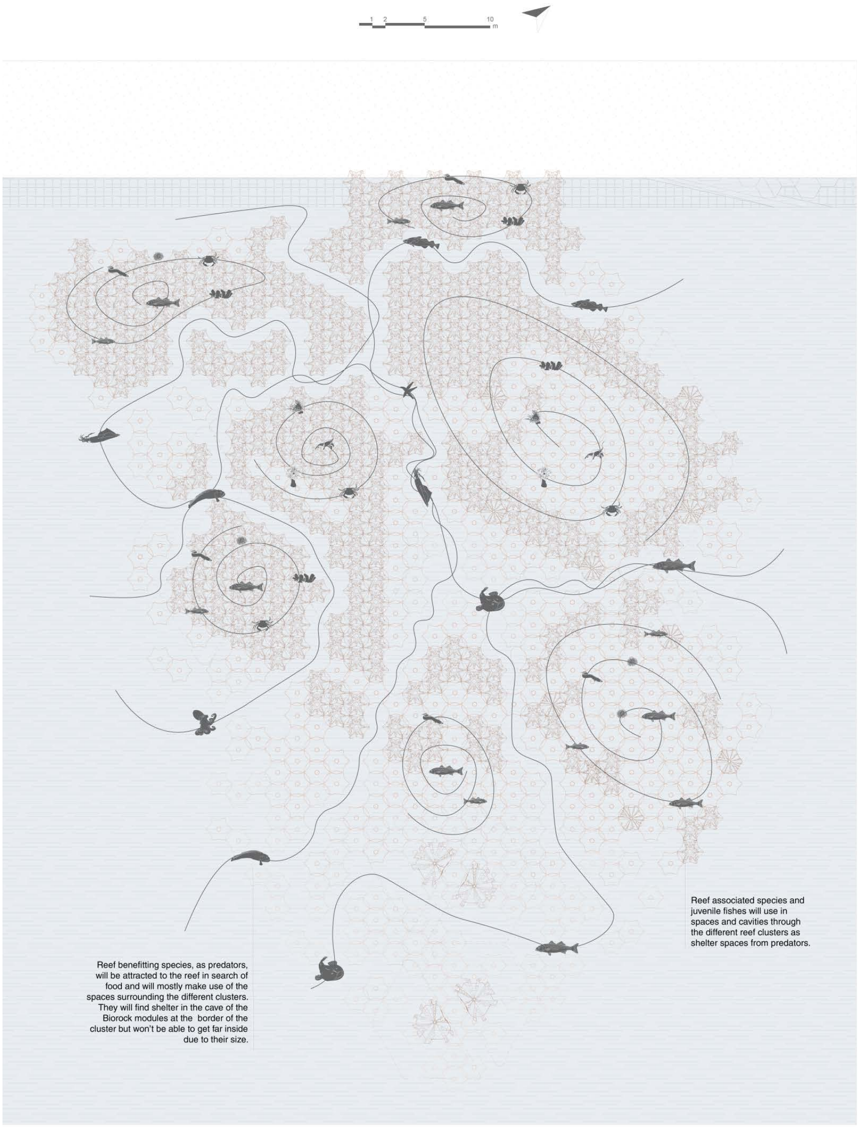


Figure 2.17
Modular Biorock column and foundation designs



Reef benefitting species, as predators, will be attracted to the reef in search of food and will mostly make use of the spaces surrounding the different clusters. They will find shelter in the cave of the Biorock modules at the border of the cluster but won't be able to get far inside due to their size.

Reef associated species and juvenile fishes will use in spaces and cavities through the different reef clusters as shelter spaces from predators.

Figure 2.18
Floorplan of the reef at high tide

Design for Coastal Ecosystems

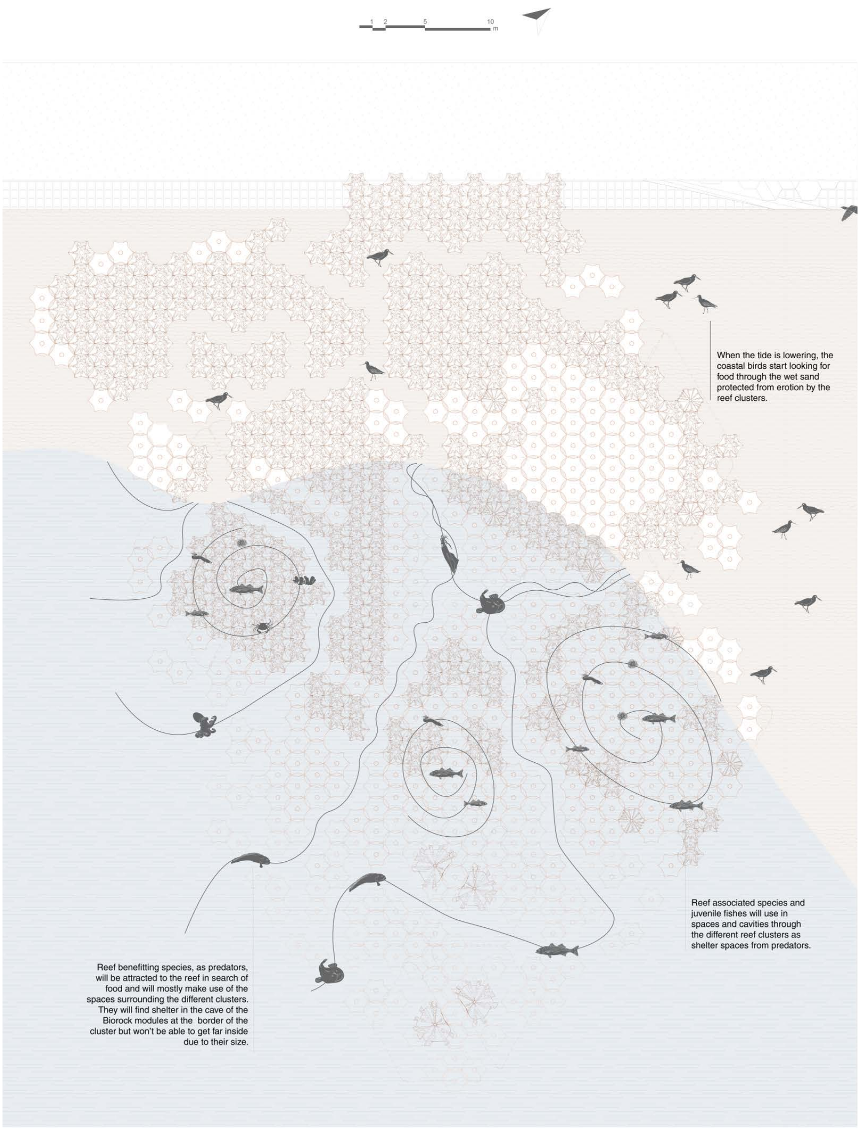
Although Biorock is primarily researched within the ecological field for its benefits to marine ecosystems, the architectural project designed in this coastal environment also considers its potential benefits for terrestrial species.

One of the major ecological challenges currently affecting the coastal ecosystem of the Oosterschelde is sand starvation, mainly caused by the reduction of tidal energy following the construction of the Oosterscheldekering. To retain sand and preserve the salt marshes and mudflats that support entire ecosystems of fish, shellfish, crustaceans, and birds, stone walls are being constructed. While these linear structures can delay the effects of ongoing sand starvation, they may not represent the most efficient solution. Current research is therefore investigating spatial designs inspired by natural patterns, consisting of assemblies of smaller structures arranged in open and irregular layouts (Van Belzen et al, 2025)

These principles influenced the design of the reef. The modules are positioned in clusters of varying shapes and sizes, allowing water currents to flow through them while reducing their strength. The project is located at the edge of the mudflat area known as the Slikken van Viane. The reef could reduce sand loss from the marsh and thereby help support its ecosystem.

Furthermore, while the submerged part of the project is specifically designed to benefit marine species, the sections located above high-tide level are intended to directly support terrestrial species as well. The Oystercatcher, along with other characteristic coastal birds of the Oosterschelde environment, depends on salt marshes and mudflats for feeding but need safe nesting grounds in the surroundings (M. Frauendorf, 2022). As many failed breeding attempts are caused by predators, providing inaccessible nesting areas could contribute to the development and protection of these species (Ro&Ad, 2023).

It is for this purpose that the roofs and Biorock columns have been designed. The roofs function as dedicated nesting areas covered with a shell substrate, while the surrounding Biorock columns create smaller enclosed spaces that can shelter nesting birds. Moreover, the open structure and porosity of the Biorock columns create habitats for insects without compromising the structural integrity of the pavilions integrated between them, thereby enriching the visitors' spatial experience.



When the tide is lowering, the coastal birds start looking for food through the wet sand protected from erotion by the reef clusters.

Reef associated species and juvenile fishes will use in spaces and cavities through the different reef clusters as shelter spaces from predators.

Reef benefitting species, as predators, will be attracted to the reef in search of food and will mostly make use of the spaces surrounding the different clusters. They will find shelter in the cave of the Biorock modules at the border of the cluster but won't be able to get far inside due to their size.

Figure 2.19

Floorplan of the reef at low tide

Design for the Visitor’s Experience

The architectural design is integrated within the reef structure to create a gradual spatial journey for visitors. The project is therefore conceived as a sequence of alternating indoor and outdoor spaces that progressively transition from the human world toward the marine environment. This results in a route connecting six pavilions distributed throughout the reef system. These pavilions are organized into four stages of spatial transition, each characterized by distinct construction principles and climatic conditions.

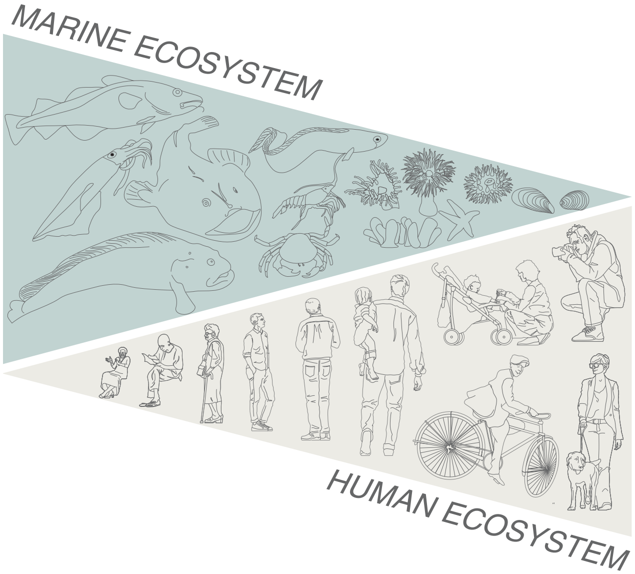


Figure 2.20

Conceptual Diagram

i. Gradient 1: Human Comfort

The entrance and café pavilions are positioned closest to the dike and at the highest elevation within the project. Their construction consists of lightweight timber structures placed on top of the reef system. In this condition, the reef functions primarily as a foundation while remaining constantly dry.

These spaces offer panoramic views over the waters of the Oosterschelde while maintaining a comfortable indoor climate. The pavilions are conceived as sheltered observation cabins from which visitors can experience the tidal landscape in comfort.

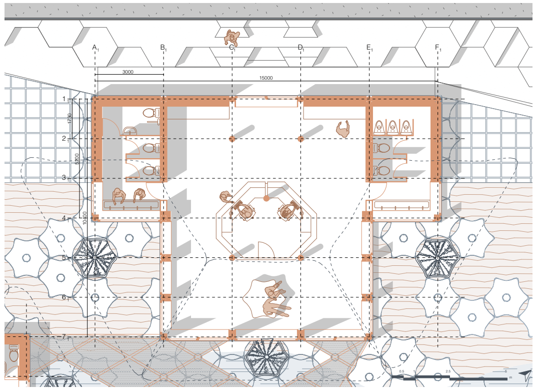


Figure 2.21

Floorplan Entrance pavilion

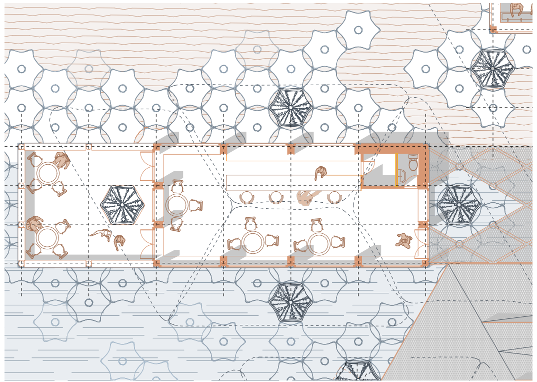


Figure 2.22

Floorplan Restaurant pavilion

Design for the Visitor's Experience

ii. Gradient 2: Sinking Within the Reef

The exhibition pavilion and research centre are partially submerged during high tide, appearing to sink into the reef structure. At this stage, the architectural and ecological systems begin to merge more directly, as the reef functions simultaneously as foundation, enclosure, and structural support.

Within the reef structure, a steel boat-like frame is inserted, inside of which a timber curtain-wall construction is assembled. Although the insulated façade still protects the interior from external climatic conditions, the filtered views through the steel framework create a more immersive and rugged marine atmosphere.

The exhibition pavilion is positioned approximately two metres within the reef structure, intentionally limiting direct outward views in order to focus attention on the interior exhibition spaces and the educational narrative. The exhibition layout encourages movement between different information displays. Similarly, the research centre organizes visitors along a linear corridor overlooking the laboratory spaces and interpretive displays, reinforcing the connection between scientific research and public experience.

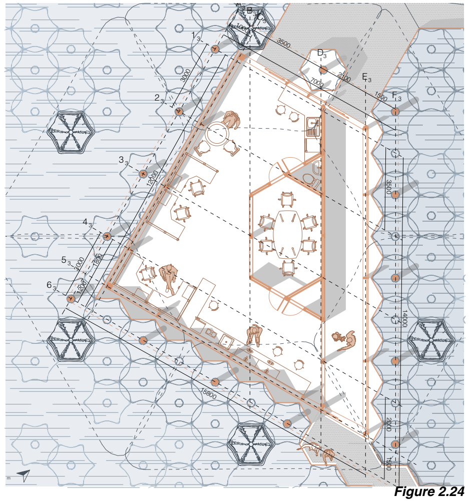


Figure 2.24

Floorplan Reserach center

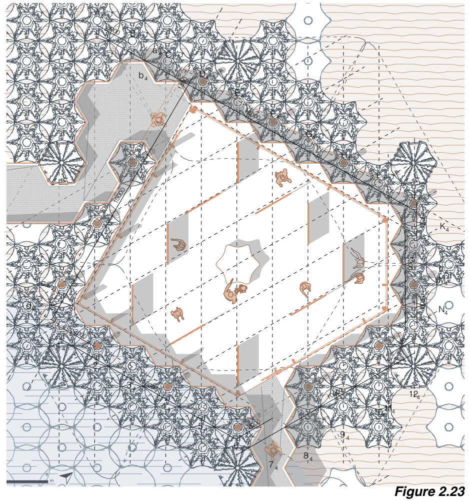


Figure 2.23

Floorplan Exhibition pavilion

iii. Gradient 3: Observing the Ecosystem

In the third stage, the pavilion is positioned entirely within the reef structure and consists solely of the exposed steel framework. Here, the architectural focus shifts once again toward the surrounding environment, this time emphasizing underwater observation.

The steel structure incorporates porthole-like openings that frame views toward the marine ecosystem. Unlike the previous stage, this space encourages visitors to remain stationary, sit, and observe the underwater environment they previously learned about in the exhibition pavilion.

As the pavilion no longer contains insulated enclosure systems, the climate inside closely resembles the outdoor environment. Wind, humidity, the smell of the sea, and the sounds of water become integral components of the architectural experience, while the Biorock columns above provide only minimal shelter and spatial definition.

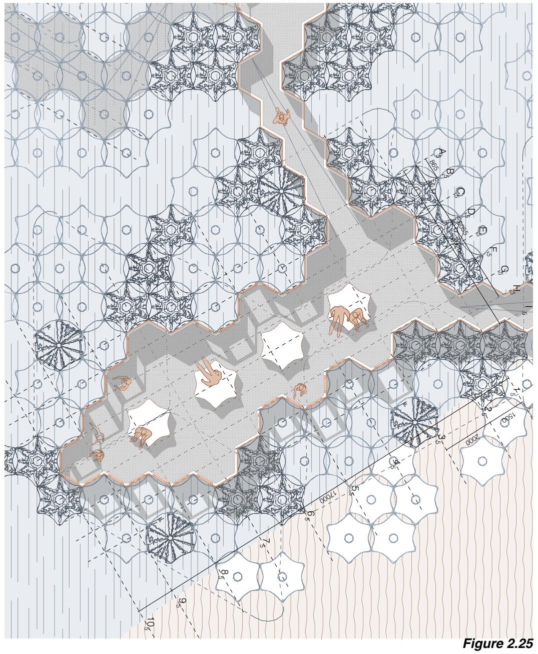


Figure 2.25

Floorplan Observatory pavilion

iv. Gradient 4: Becoming Part of the Ecosystem

The final pavilion is composed exclusively of the two reef module types between which a simple walking path is inserted. Both the path and reef structures are fully submerged during high tide, making the pavilion accessible only during low tide.

At these moments, visitors are invited directly into the habitat of the marine ecosystem, allowing them to approach the reef closely and experience the environment from within rather than from a distance. This final stage completes the gradual transition from observer to participant within the ecosystem.

Figure 2.26
Floorplan Marine promenade

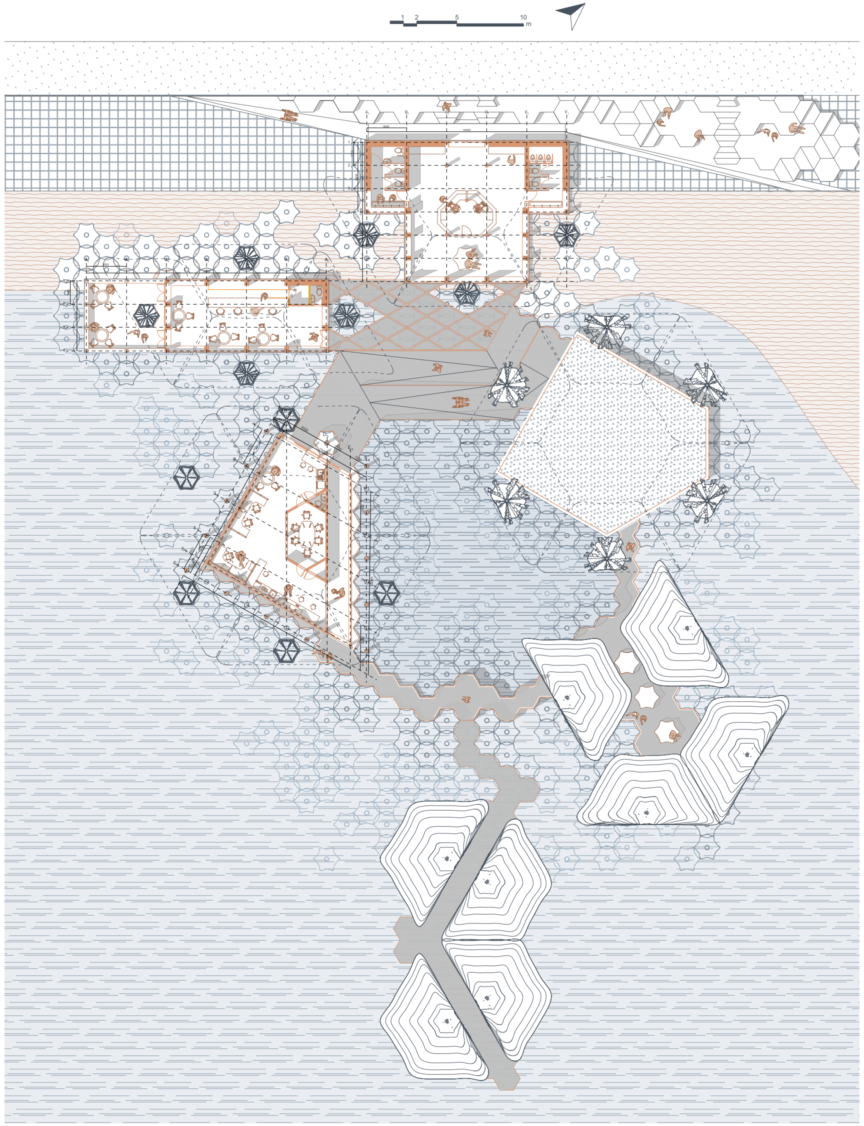


Figure 2.27
Floorplan of the upper levels of the pavilions

Designing with time

Time plays a fundamental role throughout the entire life cycle of the project.

i. Construction

Biorock is a material that requires time to grow, just as reef ecosystems themselves develop gradually over long periods. Depending on water depth and environmental conditions, the reef would be constructed in three successive layers over approximately two years (see figure 2.28).

During the installation of the final layer, wooden piles connecting the reef to the pavilion structures of the first two gradients would be inserted to allow Biorock to mineralize around the timber, gradually forming a protected fossilized wooden structure.
After approximately two years of reef growth, the pavilions would be assembled within and above the reef system to begin welcoming visitors.

ii. Use

Throughout the building's use phase, time influences the visitor experience on both short-term and long-term scales.

In the short term, the experience changes dramatically depending on tidal conditions. During high tide, the reef becomes almost entirely submerged, leaving only portions of the pavilions visible above water. These conditions create the ideal moment to observe marine life from the Gradient 3 pavilion, while the Gradient 4 pavilion remains inaccessible.

At low tide, however, much of the reef becomes exposed, allowing visitors to walk directly within the ecosystem in Gradient 4. Simultaneously, the underwater views from Gradient 3 become focused primarily on the exposed reef structures.

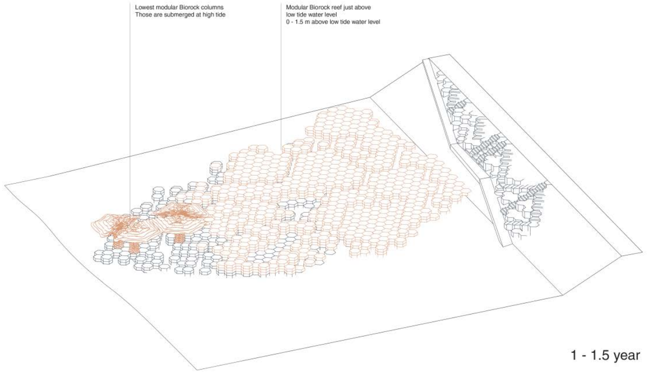
On a longer timescale, the ecosystem itself continuously evolves through seasonal changes, ecological succession, and the gradual growth of the reef structures. As biodiversity increases and the architecture ages together with its environment, the visitor experience constantly changes. No two visits are therefore expected to be entirely identical.

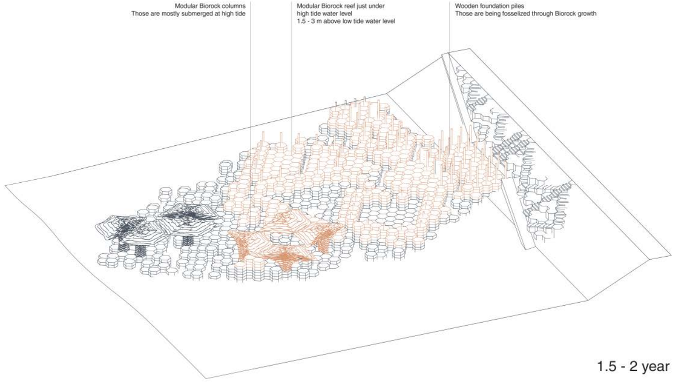
iii. Afterlife

The average lifespan of a contemporary building is currently approximately fifty years. Simultaneously, sea levels are expected to continue rising significantly over the coming century (Utrecht University, 2022). It is therefore realistic to assume that the pavilions may remain operational for a maximum of approximately one hundred years.

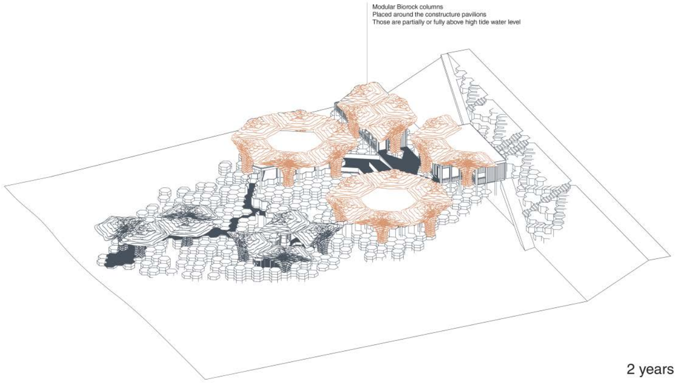
For this reason, the architectural structures are designed as modular systems that can be easily assembled, disassembled, and reused in future projects. While the architectural components may eventually disappear or be relocated, the reef structure itself can continue functioning as a living marine ecosystem.

Designing with time





Architectural Design Translation



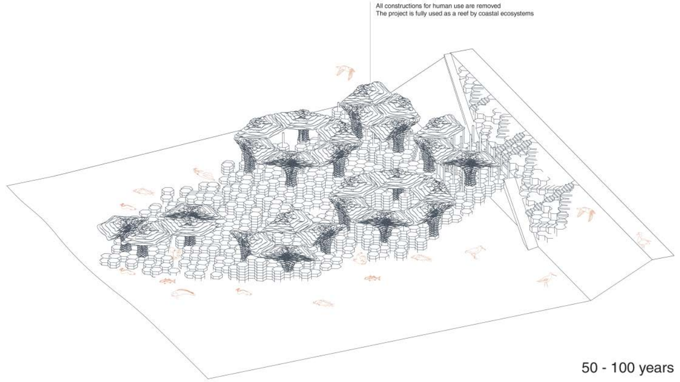


Figure 2.28

Ôde à la mer through time

III. Conclusion

Figure 3.1 Final result of column experiment (Own picture, 2026)

The initial objective of the project, Ôde a la Mer, was to investigate the translation of Biorock as a potential building material into its practical application within architecture. Due to the limited research currently available on the subject, this first exploration into its architectural implementation could have developed along many different paths.

Beyond aiming to replace conventional building materials such as concrete in order to reduce the embodied carbon of construction, the project also sought to translate the particular characteristics of Biorock into architectural design. Existing research on Biorock primarily focuses on its ecological applications within marine ecosystems. This project therefore explored the possibility that Biorock could not only help grow buildings from the sea, but also create living environments in which humans directly interact with marine ecosystems. The ambition was to develop an architecture that benefits both parties: the human world above the waterline and the marine world below it. This vision is particularly relevant within the Dutch context due to the Netherlands' unique historical and spatial relationship with the sea.

These ambitions were translated into the project's main research question:

How can Biorock technology be translated into an architectural design tool to reduce embodied carbon while integrating architecture as part of the natural ecosystem of the Oosterschelde?

The practical translation of Biorock into architecture was explored through a series of experiments, leading to conclusions regarding the most effective ways to design Biorock elements according to their material properties and growth process. The integration of Biorock with other materials was also tested during the growth process itself, revealing interesting combinations with materials such as wood and fabric. However, technical connections after growth, particularly during on-site construction, require further research and experimentation.

Within the project, Biorock was primarily used as an outer structural shell within which the different building programmes were constructed. This strategy enabled the outer elements to be designed in response to the needs of the surrounding marine ecosystem while significantly reducing the use of concrete, which remains one of the most common materials for foundations and ground floors in contemporary construction systems.

By designing modular elements that both support the ecosystem of the Oosterschelde and physically support human-built constructions, the project demonstrates a possible pathway toward the practical application of Biorock within an ethical, ecological, and future-proof architectural approach.

Nonetheless, the practical use of Biorock within the construction itself remains limited to partition walls and plaster finishes. Further research, design development, and experimentation are required to expand the applications of Biorock within our built environment.

Biorock Potential in the Dutch Context

The various experiments conducted in both aquarium and open-sea conditions demonstrated, first and foremost, the feasibility of Biorock development within North Sea conditions. Comparing the two experimental environments suggests that the most feasible and practical method for large-scale Biorock production would be direct growth in marine conditions. The aquarium experiments revealed that multiple environmental factors influence mineral accretion and material properties, with water pH proving to be particularly important. Maintaining precise control over these variables would require highly regulated production conditions, making aquarium-based fabrication relatively complex. In contrast, many of these parameters remain naturally stable in open-sea environments.

Furthermore, Biorock growth in open-sea conditions was successful and resulted in material samples that appeared structurally stronger than those produced in aquarium conditions. This difference may be linked to the complexity of natural seawater environments, including the presence of nutrients and biological interactions that are difficult to reproduce artificially. At the beginning of the summer, at the end of the experimentation time, a lot of life was also observed on the structures including juvenile mussels (see figure 3.2) These findings again support the potential of direct marine production methods.

The successful sea experiments, initiated in February when North Sea temperatures were approximately 6°C, indicate that year-round Biorock production within the Dutch marine context could be feasible.

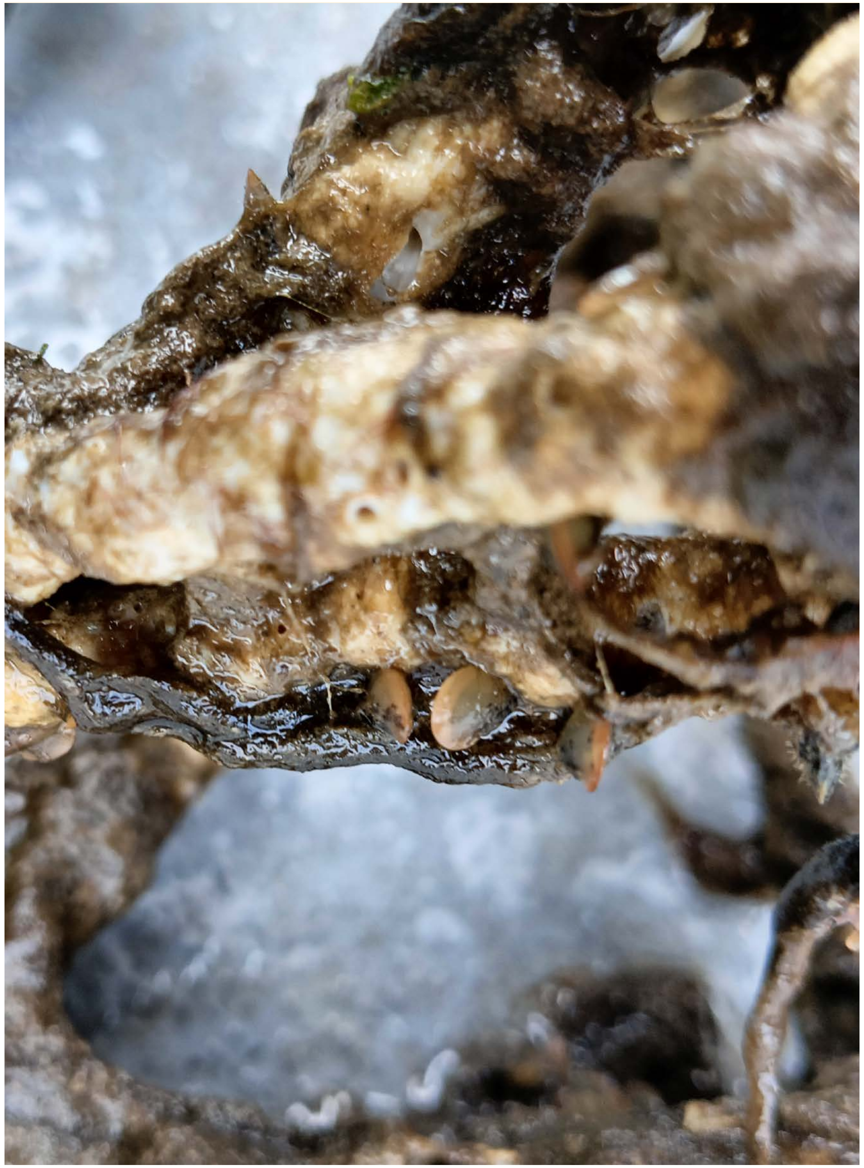


Figure 3.2
Close-up picture on grown Biorock right out of the water (Own picture, 2026)

Designing with Biorock

The experiments conducted on different steel structures and surface conditions demonstrated that structural systems should be designed to maximize the adhesion of mineral accretion to the steel framework. Without sufficient surface grip, substantial quantities of material may detach during the growth process, reducing structural performance.

Rougher steel surfaces consistently supported more effective mineral growth, while lightweight frameworks produced the most successful accretion results. The intersections within these frameworks also demonstrated significantly accelerated growth rates. Although Biorock shares certain material characteristics with concrete and may therefore appear to offer an alternative construction material, its practical architectural application should fundamentally differ from conventional concrete construction. Rather than approaching Biorock as a cast mass material, it should instead be understood as a mineralized structural system integrated into lightweight frameworks.

This alternative approach to construction introduces new architectural aesthetics shaped by both designed geometry and natural growth processes. While the underlying steel framework could be industrially fabricated and standardized, the mineral accretion process ensures that each element develops uniquely over time. As a result, the architecture visibly expresses its relationship with natural systems and environmental conditions.

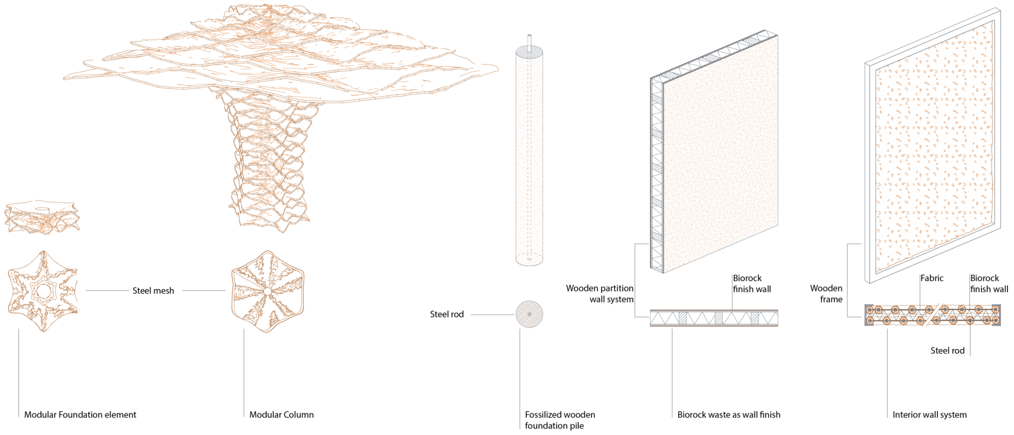


FIgure 3.3

Diagram of the use of Biorock through the project

Ecological Integration

Beyond its architectural and technical potential, this project also demonstrated the opportunity Biorock offers for designing architecture as a process of co-development with ecological systems. Rather than understanding architecture solely as a protective barrier separating humans from environmental conditions, materials such as Biorock enable the integration of surrounding ecological needs into the design process, with the potential to support and even regenerate local ecosystems.

Biorock shows particular potential for supporting marine ecosystems by creating hard substrates capable of sustaining reef-like environments. Its adaptable geometry and porous materiality may additionally provide opportunities to support life above water, including insects and bird nesting habitats.

The ecological performance integrated into Biorock architecture also has the potential to reinforce human experience and awareness of natural environments. By bringing ecosystems closer to human activity, architecture can actively contribute to ecological awareness and environmental stewardship. Within this project, the boundary between human and non-human environments was intentionally blurred, gradually bringing both together through the architectural design. In doing so, the project explored the potential of architecture to function simultaneously as habitat, educational interface, and observation instrument.

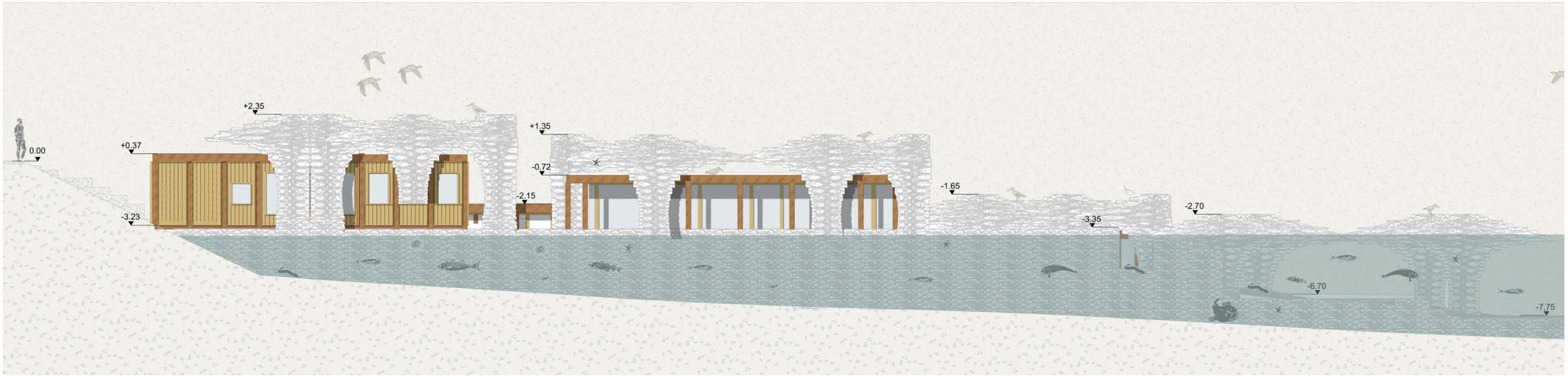


Figure 3.4
South West Elevation

Time as an Architectural Tool

The relatively slow growth process of Biorock requires designers to think on longer temporal scales while simultaneously offering the opportunity to integrate time itself as an architectural tool. Rather than considering buildings as fixed and completed objects, Biorock encourages an architectural understanding in which structures continuously evolve through material growth, weathering, and ecological succession.

Combined with the natural seasonal transformations of ecosystems, this process redefines architecture as an ever-changing spatial condition rather than a static object. Time therefore becomes an active design parameter, shaping both material formation and spatial experience throughout the life of the project.

This research demonstrates that Biorock has the potential to function both as a low-carbon building material and as an ecological design strategy, enabling architecture to evolve from a static object separated from nature into a living system that develops together with its environment.

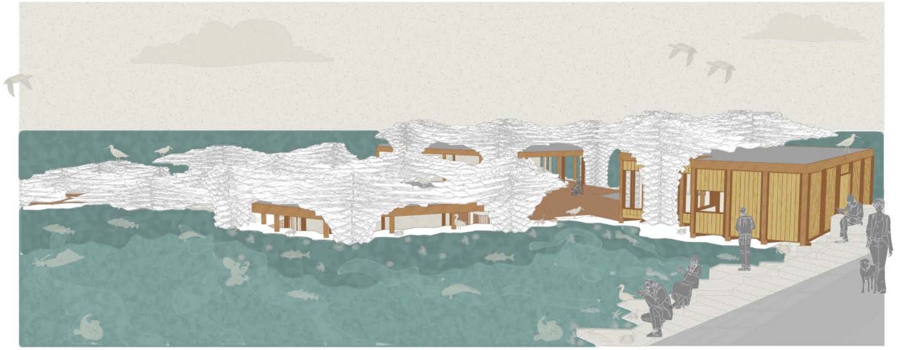


Figure 3.5
Impression from the dike at high tide

Figure 3.6
Impression from the dike at low tide

Limitations

Although the research was primarily based on experiments supported by existing literature, current knowledge regarding Biorock remains limited, and many additional structural, ecological, and architectural investigations are still required. Due to time constraints, the project necessarily relied on several assumptions that would require further scientific validation. The limited timeframe also restricted the experiments to relatively small scales and short durations. While the sea experiments were conducted over a period of four months, full-scale construction elements would likely require growth periods of one to two years. Upscaling the experiments would therefore be necessary to evaluate realistic structural applications and construction feasibility.

Furthermore, although the relatively slow growth process can be interpreted architecturally as a design opportunity, it also remains a practical limitation within conventional construction timelines. When considering Biorock applications outside marine environments, factors such as framework fabrication, growth-site logistics, transportation, assembly, and future maintenance would need to be integrated into the design process from the earliest stages.

Another important limitation concerns the material's ecological impact. Biorock is frequently discussed as a possible substrate for reef restoration and is widely recognized for its positive ecological effects in tropical marine environments. However, scientific research regarding its ecological performance within Dutch marine ecosystems has only recently begun. Initial studies suggest promising potential, but further long-term ecological research is required to evaluate its actual environmental impact and guide future ecological design applications more accurately.

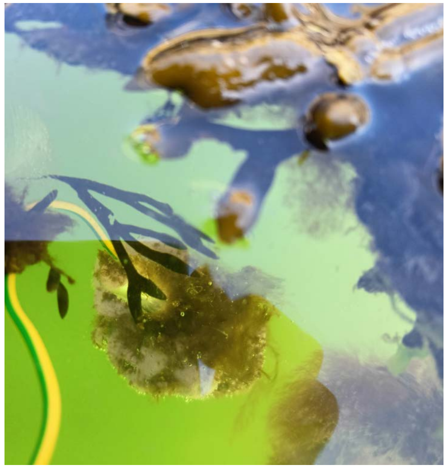


Figure 3.8
Picture of experimental structure in sea water

Reflection

Although the project aimed to develop a comprehensive understanding of Biorock and its architectural potential, several assumptions still had to be made due to time limitations. The research demonstrated that Biorock is a material with significant potential for further investigation, particularly regarding practical architectural applications. Previous literature has mainly focused on the material properties and ecological benefits of mineral accretion, while this project explored an initial translation of these qualities into architectural and spatial applications. However, these fields still require further integration.

The conducted experiments provided insights into growth behavior, aesthetic qualities, and potential ecological benefits, but additional structural testing of the different systems would allow for a deeper understanding of their performance. Further research into practical construction methods and material connections would also strengthen future architectural applications.

Architecture is a puzzle that brings together many different perspectives, stakeholders, users, and contextual conditions. This project attempted to approach that puzzle with Biorock as its central element. Because the material touches upon such a wide range of disciplines, the complexity of the project became extensive. Each field introduced an interesting layer to the research; however, due to time constraints, many of these aspects would benefit from further investigation and understanding.

When transitioning from research to design, I relied on the information collected through interactions with various experts and attempted to translate these insights into architecture. It could have been valuable to maintain closer collaboration with some of these experts throughout the design process, as their continued feedback might have further enriched the translation of the research into the final architectural proposal.

Ultimately, this project brought together multiple perspectives on the possibilities that mineral accretion could offer to the field of architecture. It represents an initial step toward the development of a built environment in which architecture not only serves human needs, but also actively contributes to ecosystems and landscapes.

Figure 3.9
Model Design experiment

Acknowledgements

This research and design project focused on the highly specific material of Biorock. To better understand its particularities, I had the opportunity to engage with Tom Goreau, a marine biologist with extensive experience working with Biorock, and Cameron Penney, who graduated with a Master of Architecture from Carleton University and explored the architectural opportunities that Biorock could offer. Their experience shaped the beginning of my project, and I am deeply grateful for their availability, their willingness to answer my questions, and the ideas and feedback they provided.

The limited amount of existing knowledge available on the subject also led me to investigate across a wide range of disciplines. Through the process of understanding Biorock, I engaged with professionals from diverse fields. These included civil engineers discussing the technical investigations required for practical applications, such as Henk Jonkers; chemical engineers explaining the electrochemical processes behind mineral accretion, including Marc Koper; coastal engineers outlining the challenges faced by the Dutch coastline under climate change, such as Rosh Ranasinghe; marine ecologists specialized in the Oosterschelde who provided insights into the ecological challenges and ongoing research within this unique environment; and architects specialized in the integration of ecosystems into building design, including Jim van Belzen.

In addition to the theoretical research regarding the material and context of the project, I had the opportunity to set up two types of experiments to better understand the growth process. These experiments formed a core part of the project, and thanks to The Green Village, which provided both space and facilities, I was able to conduct my aquarium experiments.

For the seawater experiments, I was very fortunate to come into contact with marine biologists from Wageningen University & Research, Joop Coolen and Enzo Kingma, to whom I am deeply grateful. Thanks to their support, I was given the opportunity to conduct growth experiments directly in seawater near the coast of Texel, which greatly enriched both my understanding and the scope of the research. These experiments were carried out under highly controlled conditions, with carefully regulated electrical currents and professionally assembled electrical circuits developed with the assistance of CORROSION. Their expertise and support, including access to laboratory facilities and explanations regarding the challenges of seawater electrolysis, were invaluable to the realization of the experiments.

Finally, throughout the entire research and design trajectory, I was supported by my professors Geert Coumans and Marcel Bilow, whose feedback and guidance helped shape both the research direction and the architectural development of this challenging project.

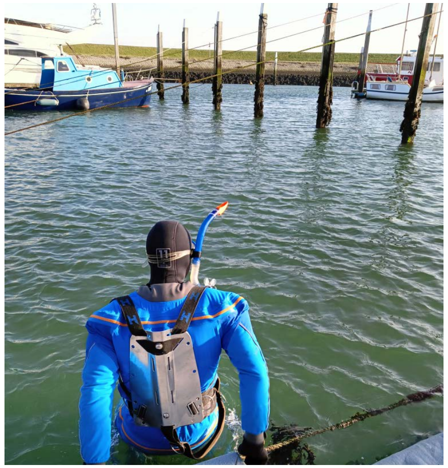


Figure 3.10

Experimenl retrievalTexel

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Appendix I
Material Technicalities

Appendix 1: Biorock, Material Technicalities

Material production

An anode positively charged and a cathode negatively charged create precipitations of some of the elements dissolved in seawater (Mg^{2+}, Ca^{2+}) on the cathode resulting in a deposition of Calcium Carbonate ($CaCO_3$). For the anode a special non-corrodible and non-toxic material must be used (Goreau, 2012).

We can distinguish two types of Biorock, one produced using a low voltage (LV), around 2.5V, with a minimum of 1.23V (Goreau, 2012) and one using a high voltage (HV), around ???V. That difference in voltage influences the growth rate of the material with LV growing around 0.8 cm/year compared to 5.5 /year for a HV Biorock (Johra, et al. 2021). The difference in voltage also creates different crystal forms formed by the calcium carbonate. When increasing the current in the electrodes above a certain level results, the pH at the surface of the electrode is increased. Reaching a pH of 9.2 results in the electrodeposition of magnesium hydroxide ($Mg(OH)_2$), known as Brucite, rather than $CaCO_3$. Brucite is a softer mineral than Aragonite and Calcite.

Chemical process

When a voltage of a minimum of 1.23V, the water is broken down at the anode to make oxygen gas and hydrogen ion, making the local environment both oxidizing and acidic (Goreau, 2012). An acidic environment is one where the concentration of hydrogen ions (H^+) is relatively high, making the pH less than 7.
That environment favors proton donation while an oxidizing environment favors electron loss. Therefor, the first reaction taking place at the anode is the following:

$$2\,H_2O \longrightarrow O_2 + 4\,H^+ + 4\,e^- \tag{1}$$

At the cathode the water is broken down to make hydrogen gas and hydroxyl ion, making the local environment both alkaline and reducing (Goreau, 2012). An alkaline environment is the contrary of a acidic one. It is an environment where the concentration of hydroxide ions (OH^-) is relatively high, giving the solution a pH greater than 7. A reducing environment is a one that favors reduction reactions substances and tend to gain electrons rather than lose them. Therefor, the first reaction taking place at the cathode is the following:

$$2\,H_2O + 2\,e^- \longrightarrow H_2 + 2\,OH^- \tag{2}$$

When combining the reactions taking place at the anode and cathode the net reaction for charge and pH balance is the following:

$$6\,H_2O \longrightarrow 2\,H_2 + O_2 + 4\,H^+ + 4\,OH^- \tag{3}$$

The oxygen produced at the anode provides organisms in surrounding areas with this essential element and acts to reduce anoxia and dead zones in the ocean (Goreau, 2012).

The Hydrogen ions produced at the anode dissolve in the water until they react with the limestone sediments in surrounding areas and are neutralized:

$$H^+ + CaCO_3 \longrightarrow Ca^{++} + HCO_3{}^- \tag{4}$$

On the other hand the hydroxyl ions produced at the cathode react with dioxide carbon to produce as well bicarbonate ions:

$$CO_2 + OH^- \longrightarrow HCO_3{}^- \tag{5}$$

Then the bicarbonate ions produced at both cathode and anode react the hydroxyl ions at the cathode into the precipitation of limestone directly on the cathode surface:

$$HCO_3{}^- + OH^- \longrightarrow CO_3{}^{2-} + H_2O \tag{6}$$

$$Ca_2{}^+ + CO_3{}^{2-} \longrightarrow CaCo_3\,(s) \tag{7}$$

When the current is at high density, the mineral forms is in the form of Brucite which removes hydroxyl ion wihtout converting bicarbonate to carbonate ion. It also reduces the amount of CO_2 produced by limestone deposition:

$$Ca^{++} + 2\,HCO_3{}^- \longrightarrow CaCO_3 + H_2O + CO_2 \tag{8}$$

Therefor brucite formation has a net effect of reducing the effects of ocean acidification cased by increased CO_2 in the atmosphere.

Above 1.36V another side reaction happens at the anode which converts chlorine to chlorine gas:

$$2\,Cl^- \longrightarrow Cl_2 + 2\,e^- \tag{9}$$

It is almost impossible to get to a voltage between 1.23 and 1.36 but the lower the voltage the less chlorine gas is produced.
The will always be a far more oxygen production than chlorine however chlorine can build up in closed systems like aquaria or tanks and pose problems (Goreau, 2012).
In ocean chlorine is rapidle neutralized by reaction with dissolved organic matter. Furthermore, it was observed that that chlorine reaction does not pose problems for life in the ocean with fish and coral growing well when being further than 1 to 2 mm from the anode (Goreau, 2012).

Experimentation set-up

The material can be grown in an experiment either directly in the sea or in an aquarium. The easiest setup is to grow the experiment in an aquarium, although this will not demonstrate the interaction between growth of the material and nutrients and living species that could be found in the sea. Another disadvantage of an aquarium experiment is that the concentration of minerals needed for the chemical reaction diminishes over time, whereas the water is constantly renewed in an experiment conducted directly in seawater. However, as aquarium experiments are the easiest and fastest to set up, they are the most likely to be used.

Maximum precipitation /L of seawater

The limit of the reaction is the alkalinity, not the calcium dissolved in the water. Typical seawater, with a salinity around 35, has [$Ca_2{}^+$] concentration of around 10.28 mmol/kg.
The total alkalinity (TA) is the controlling inventory for how much carbonate can be turned into solid carbonate. A typical total alkalinity for the sea at the Dutch shores is around 2.40 mm/kg (Norbisrath, 2024).
A precipitation of 1 mol of $CaCO_3$ removes 2 equivalents of alkalinity. So the maximum moles of $CaCO_3$ equals to $\frac{TA}{2}$.

Constants

- Molar mass $CaCO_3$ = 100.0869 g/mol

$Ca_2{}^+$ = 10.28 mmol/kg

- TA = 2.40 mmol/kg
- Sea water density = 1.025 kg/L

Converting to mol/L

- $$[Ca_2{}^+] = 1.28 \times 1.025 = 10.537 mmol/L = 10.537 \times 10^{-3} mol/L$$
- $$TA = 2.4 \times 1.025 = 2.46 mmol/L = 2.46 \times 10^{-3} mol/L$$

The Calcium carbonate amount being limited by the TA the maximum precipitation of calcium carbonate per liter of sea water should be as following:

$$[CaCO_3 = \frac{TA}{2} = \frac{2.46 \times 10^{-3}}{2} = 1.23 \times 10^{-3} mol/L$$

Converting into mass of maximum Calcium carbonate precipitation per liter of seawater:

$$m_{CaCO_3} = 1.23 \times 10^{-3} \times 100.0869 \approx 0.123 g/L \approx 123.11 mg/L$$

Mechanical properties

For Biorock to be used as a building material its mechanical properties need to be known. Biorock as building material has only been considered for a few years and the research are therefor currently limited. The first research made experiments on grown biorock elements and compared those results to results obtained with normal weight class concrete samples. Different experiments were made to test the different mechanical properties of the material.

Density

Hicham Johra (2021) made a comparative research between HV and LV Biorock highliting the difference in mass of the different mineral forms of Calcium Carbonate (Table 1)

Mineral	LV Biorock (mass in perc)	HV Biorock (mass in perc)
Aragonite	80.8	46.6
Brucite	18.9	52.3
Calcite	0.3	1.1

Table 1: Quantitative composition analysis of the low-voltage and high-voltage Seacrete materials (Johra, et al. 2021)

When comparing measure density and solid density of both materials a higher density of HV Biorock is highlighted (Table 2). When compared to a normal weight class concrete around 2400 kg/m^3

	LV Biorock (kg/m^3)	HV Biorock (kg/m^3)
Measured density	2499.2	1771.1
Solid density	2700.0	2540.0

Table 2: Measured and Solid density comparison (Johra, et al. 2021)

Mechanical properties

As shown before HV Biorock is mainly composed of calcium carbonate in the form of Brucite which is a form with a high porosity and therefore a weaker resistance in its mineral matrix (Johra, et al. 2021).

Penetration test on 1 x 1 x 0.4 cm samples

- LV : 3.9 kN
- HV : 1.4 kN
- Concrete : 3.4 kN

The compression resistance is thus significantly lower than the one of the concrete sample, but it is within the range of compression strength class C12/15 which is the minimum for application if there is no risk of corrosion or attack. On the other hand, it can be observed that the compression strength of the LV Biorock is similar to the one of the tested concrete, and it could therefore be compared to a strength of class C20/25.

Thermal properties

Other than mechanical resistance comparison, a knowledge of the thermal properties of the material is needed to be able to apply it in the best way in a building. Therefore, different types of properties need to be listed.

Specific heat capacity

Both types of Biorock, LV and HV have a specific heat capacity very close to the one of calcium carbonate minerals Aragonite and Calcite as those are its the main minerals.
At room temperature the specific heat capacity of Biorock is ranging between 800 abd 1200 J/kgK. It can therefore be assumed that Biorock has a specific heat capacity very similar to concrete, natural stones and ceramic materials of equivalent density (Johra, et al. 2021).

Thermal diffusivity

Due to a 29% lower bulk density of LV Biorock, the thermal diffusivity of HV Biorock is significantly lower than the one of LV.
LV Biorock has a thermal diffusity within the range of typical natural stone and concrete materials or similar density and have a thermal diffusivity ranging from 0.3 to 1.6 mm^2/s (Johra, et al. 2021).

Thermal conductivity

Due to the difference in porosity between LV and HV Biorock, HV Biorock has a significantly lower thermal conductivity than LV Biorock. Indeed the measured thermal conductivity between 10 and 60 degrees C is as following:

- LV: 1.4 - 1.5W/mK
- HV: 0.65 W/mK

Moisture absorption - desorption capacity

As HV Biorock has the largest and/or most connected open pores it is therefore expected to have the highest potential for moisture buffering (Johra, et al. 2021).

Summary

The results from the experiments made through the research of Johra et al (2021) the following assumptions can be made for the characteristics of Biorock as a building material (Table 3).

Property	LV Biorock	HV Biorock	Concrete
Density (kg/m^3)	2499.2	1771.1	1800 - 2400
Compression Strength (MPa)	not meas7ured	16.8	24.2
Puncture resistance (kN)	3.9	1.4	3.4
Specific heat capacity (J/kg.K)	811	908.2	900
Thermal diffusivity (mm^2/s)	0.69	0.45	0.99 - 0.67
Thermal conductivity (W/m.K)	1.398	0.654	1.95 - 1.33

Table 3: Summurize resulted mechanical propertie of Biorock (Johra, et al. 2021)

Appendix II

Material Growth Analysis

The experiments in the aquarium were close to daily controlled on several factors. The growth itself was measured by weighing the structure. The weight was compared to the starting weigh of the structures and changes in growth rates were observed through the process in time. These growth rates were then linked with the other measured factors investigating the environment the material is growing in. For that purpose, the water temperature, pH and the specific gravity (SG) were kept track of.

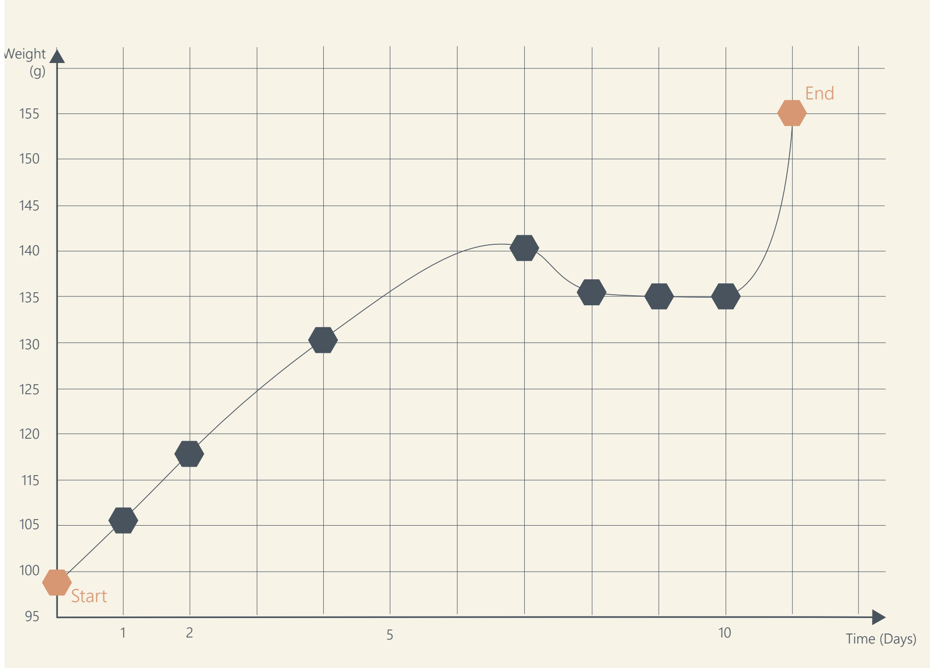
Water temperature

The temperature of the water was an interesting factor as most projects using Biorock up to now were concentrated in the tropical waters of Jamaica to Indonesia. In the aquarium the temperature ranged between 11 to 15 degrees Celsius. The aquarium being placed near a heater and behind a window exposed to the east, the water temperature varied depending on the weather and the setting of the heating. Therefor when the sun was shining and the heating was on the water temperature usually rose to 15 degrees Celsius, but when the heating was off, in the weekends, the temperature decreased to around 11 degrees Celsius. Even though these temperatures varied from day to day, no clear effect on the growth rate could be observed. We can therefor conclude that water temperatures above 10 degrees Celsius are sufficient for the growth process of Biorock to happen but in a range of 5 degrees the correlation between temperature and growth rate cannot be proven.

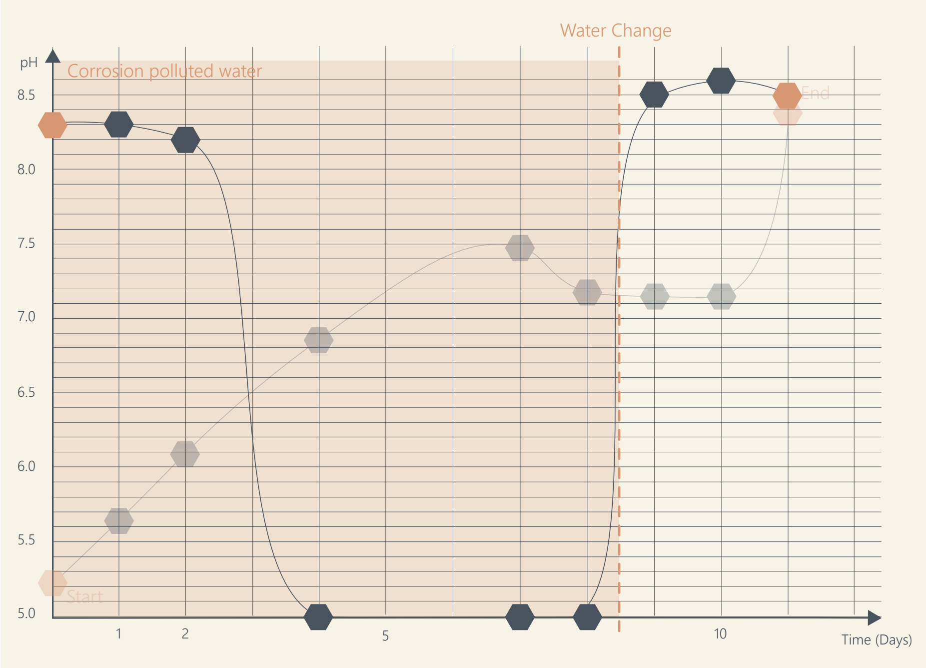
pH

The pH of the water is the factor that has been showing the most important correlation with the growth process of the material Biorock. While in the sea the pH of the water is a constant value, around 8.2 in the Northen Sea (Waddenvereniging, 2011), in the aquarium where the experiments were proceeding the pH was a highly varying factor. Indeed, as there was no movement and renewal of the water in a limited amount of water, around 100L, the pH could easily be changed by different factors. These variations showed, compared to the temperature, interesting correlation with the growth rate of Biorock.

With the starting experiment an important decrease in the pH was observed within the first two days going from 8.2 to 5. Different explanations to this decrease were tested, first by adding salt which brought the pH back to 7. The salinity of the water showed to be at least not the only factor as a few days later the pH was back to 5. The conclusion was set that the acidity of the water was due to the corrosion of the first



Graph 1: Weigth Analysis Experiment 1 (own graph)



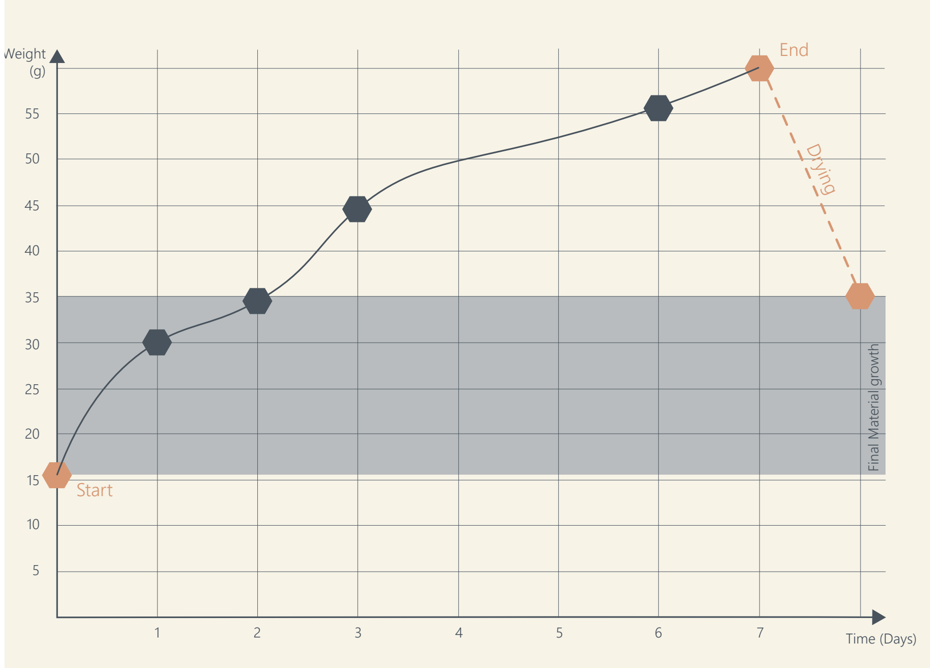
Graph 2: pH Analysis Experiment 1 (own graph)

anode which was made from steel. That anode was quickly changed to a titanium with MMO coating anode, preventing any further corrosions. The most important observation from this pH decrease was the effect it had on the Biorock growth as that one started decrease with the acidity of the water. A conclusion can therefor be drawn that the calcium carbonate dissolves more rapidly than it grows in acid water. The experiment made showed that the growth rate was most effective with a pH between 7 and 9.

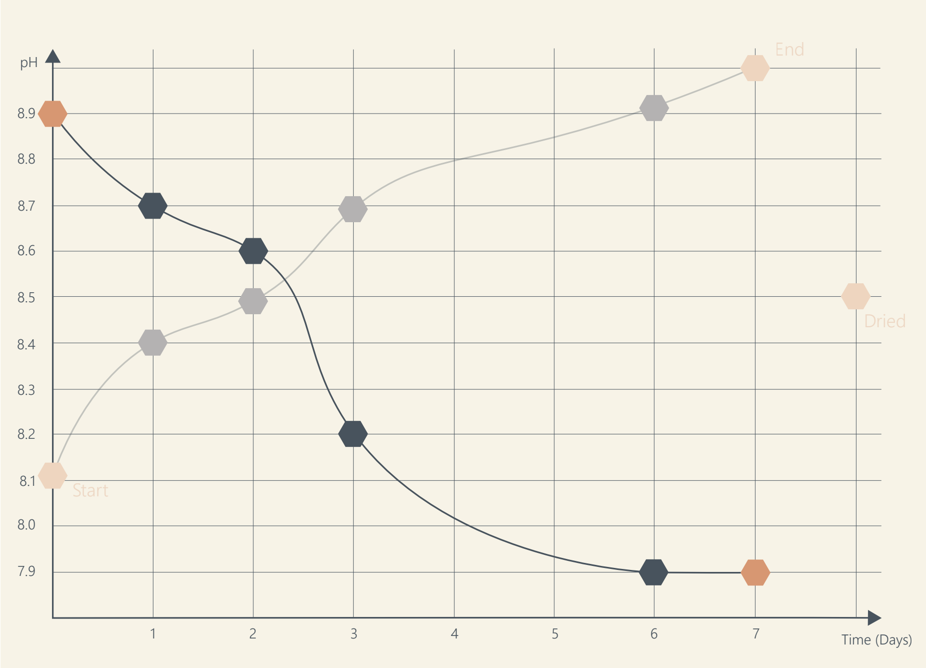
Not only did the experiments show that the pH had an influence on the growth rate of Biorock, but it also showed the impact of the chemical process on the pH of the water. Indeed, while the material was growing a correlation can be made with the slow decrease of the pH in the water of the aquarium (graph ...). A constant pH value showed to have the best effect on the growth rate but in still restricted amount of water that value will automatically be influenced by the chemical process and become slowly more acid.

Specific Gravity

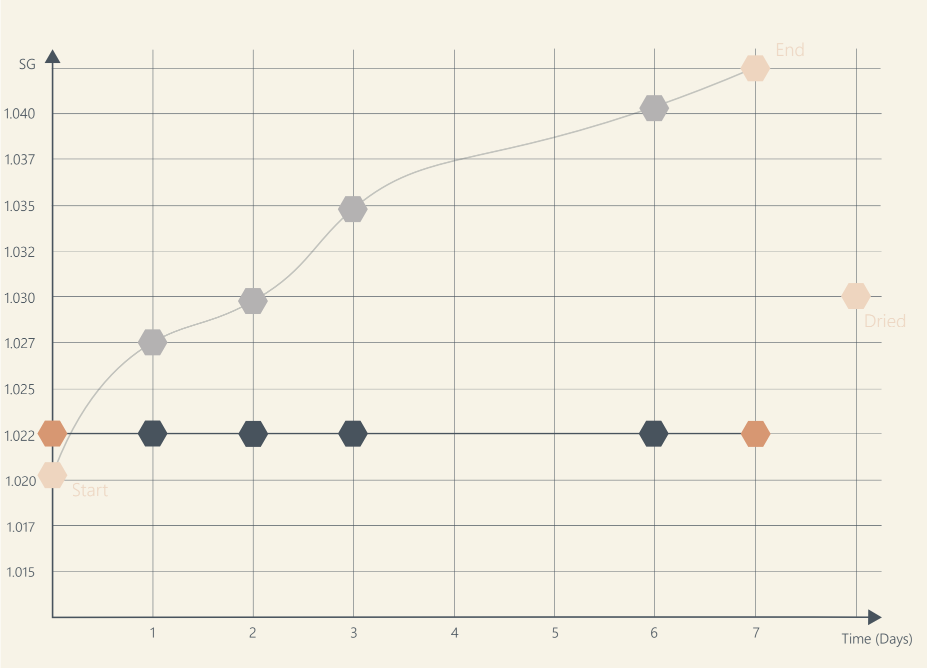
The specific gravity, or relative density, of the water was mainly measured to check the salinity of the water. Specific gravity of sea water is between 1.020 and 1.030 and the North Sea has a specific gravity of approximately 1.027 (McCombs et al., 1928). That value varies depending on the temperature of the water and due to the chemical reaction of the Biorock growth using minerals of the sea water the salinity will naturally slowly decreased. The aim is to keep the value constant, to reproduce as much as possible the open sea conditions. The



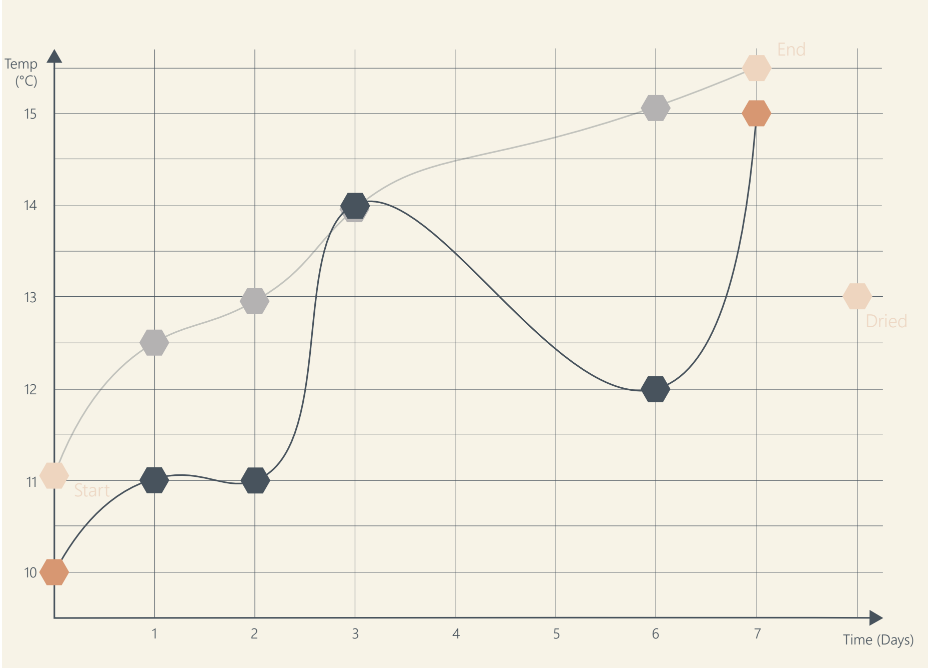
Graph 3: Weigth Analysis Experiment 2 (own graph)



Graph 4: pH Analysis Experiment 2 (own graph)



Graph 5: Specific Gravity Analysis Experiment 2 (own graph)



Graph 6: Water Temperature Analysis Experiment 2 (own graph)

value was therefor measured to know when and how much new salt should be added to the aquarium water.

The salinity of the influencing the amount of minerals available for the chemical reaction, the effect of its value is known to have an impact on the Biorock growth. The specific gravity often aimed for, with a low water temperature between 10 and 15 degrees Celsius, was 1.022. When that value was brought to 1.030 after an addition of salt the growth the Biorock did not seem to be highly impacted. But as the aim of the experiment wasn't to test the effect of salinity on the material growth no clear conclusions can be drawn from these observations.

Conclusion

The production of Biorock as a possible building material if done in a closed environment like an aquarium will have to be very well controlled on factors that will automatically vary due to the chemical reaction of the material growth. These factors would have to be constantly measured and adapted to mimic sea conditions. These sea conditions are indeed probably the most effective ones for the chemical process of the material growth. The salinity for exampled but also the pH, being of 8.2 in the North Sea. When looking at the future, the seas will probably become more acid due to the increase of carbon dioxide in the air. The pH of the North Sea is therefor expected to decrease to 7.8 for 2100 (Waddenvereniging, 2011). That value would still be in the right range for Biorock production, but slow acidification of the sea might have an impact on the growth on the long term.

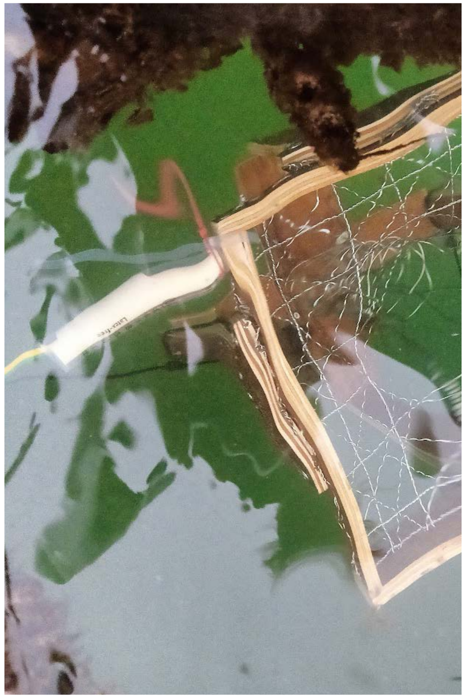
Moreover, as the temperature of the water does not seem to limit the material growth, Biorock production might be more effective and easier to implement directly in open sea waters.

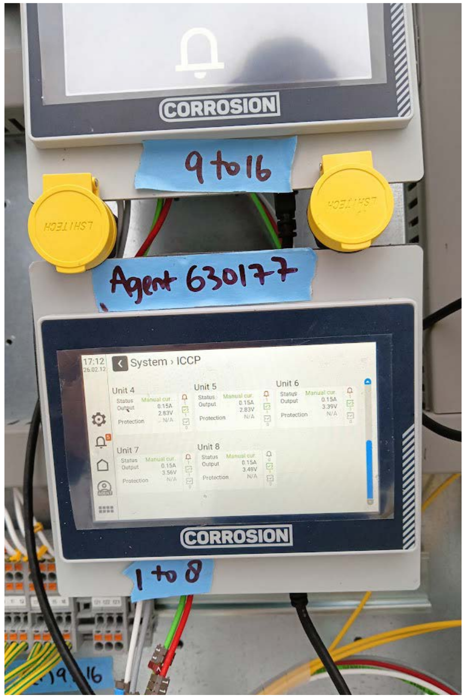
Limitations

The experiments made in the aquarium were on a quite tide budget bringing some technical aspects that might have influenced the material growth and could be improved for better results.

The first limitation was on the power supply which determined the current and voltage values going through the electric circuit. An optimum situation would be to have a constant voltage around 3V or current around 0.15. Those values are known as enabling a material growth with a high percentage of aragonite compared to brucite, resulting in the strongest form of Biorock. But no full control could be obtained over these values in the experiment. The power supply being set on the minimum often was more between the 4 and 5V and could jump to higher values with no clear explanation. Those changes did have impacts on the properties of the grown material which showed different results from the one experiment to the other.

A second limitation was in the stagnation of the aquarium water which in better circumstances would have been brought in movement or even better, would have been constantly renewed. This brought difficulties mainly on the pH of the water which turned out to be a very important factor in the material growth as shown before. These limitations explain that the growth environment might not have been very comparable to open sea conditions and explains different observations on the material growth in the open sea experiments.





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System › ICCP

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Protection  N/A

Unit 5
Status      Manual cur.
Output      0.15A
            2.83V
Protection  N/A

Unit 6
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Protection  N/A

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Protection  N/A

Unit 8
Status      Manual cur.
Output      0.15A
            3.48V
Protection  N/A
```

Open Sea Experiements

Compared to the aquarium experiments, environmental conditions in the open sea were considerably more stable. Parameters such as salinity and pH could be considered nearly constant, with a specific gravity of approximately 1.027 and a pH around 8.2. Water temperature also remained relatively stable on a daily basis and varied mainly with seasonal changes, which may provide better opportunities to observe long-term effects on material growth.

Control over the electrical parameters was also improved in the open sea experiments. The current in the electrical circuit remained constant at approximately 0.15 A, resulting in only small variations in voltage, which remained around 3 V. In addition, the electrical connections were specifically adapted to seawater conditions with the assistance of CORROSION, which enabled reliable operation and improved control of the system. As a result, the material growth observed in the open sea experiments is likely closer to the conditions required for the intended material properties.

The open sea experiments also aimed to explore the influence of nutrients present in seawater on the development of the material. Although the comparison with the aquarium experiments is limited by other varying factors, the interaction between the chemical growth process and marine life remains an important aspect to observe.

During the first weeks of growth in open sea water, the material already showed visible differences compared to the aquarium-grown samples. In particular, the material displayed a different colour, which may be related to nutrients present in the seawater that become incorporated during crystallisation. In addition, early signs of biological colonisation were observed, including the growth of algae on the material surface, indicating the first stages of marine flora developing on the structure.

Appendix III

Design Experimentations

I. Surfaces

Hypothesis

The first experiment was designed to investigate the effect of different surface types on Biorock growth. Previous research conducted by Wageningen University reported that Biorock grown on steel surfaces tended to peel off, preventing the accumulation of thicker material layers. In their experiments, the steel surfaces were smooth, flat, and positioned vertically. This observation led to the hypothesis that surface profile and roughness influence the adhesion of the growing material.

Design

To test this hypothesis, an experimental structure containing a variety of surface types was designed, and the resulting material growth was observed.

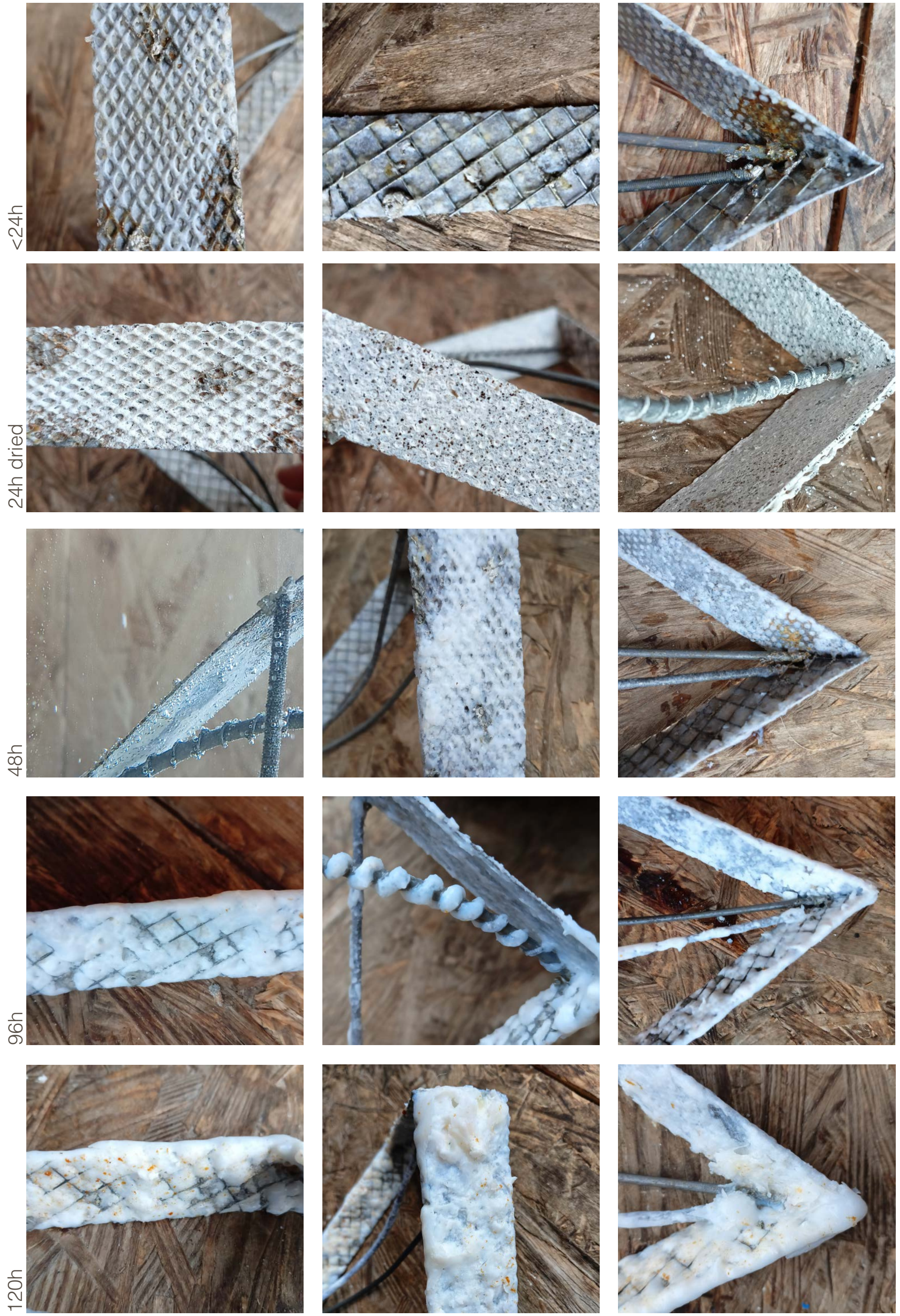
Conclusions

The smooth, flat surfaces showed the same behaviour reported in previous research, producing thin material layers that detached easily. In contrast, rougher surfaces appeared to promote faster and more stable growth. This may be explained by improved adhesion to the base surface, which reduces the loss of deposited material.

The profile of the structure also showed a clear influence on material growth. Smooth steel wires exhibited relatively limited deposition, whereas two wires entangled together showed significantly greater material accumulation. These results suggest that structural complexity and increased surface contact enhance the attachment and development of Biorock.

Based on these observations, subsequent experiments primarily used structures made from entangled steel wires in order to reduce steel use while optimising Biorock growth.

Aquarium



II. Branch Structure

Hypothesis

The second experiment focused on the shaping of the resulting material. The aim was to identify a method for shaping a thin and relatively weak steel structure, using the minimum amount of steel, which could subsequently be strengthened through the growth of Biorock.

Because Biorock forms through an organic growth process, design inspiration was taken from natural shapes and structures. This experiment explored the possibility of using irregular wooden branches—materials that are normally unsuitable for structural construction—as temporary supports to guide the shape of the steel framework.

Design

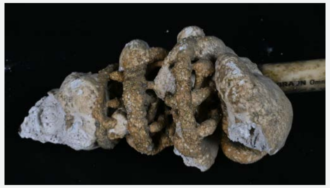
For the experiment, entangled steel wires were placed around a wooden branch. The Biorock growth occurred relatively quickly, gradually covering the branch as the mineral layer developed. The material that formed directly on the wood showed some colour variation, likely caused by organic compounds from the wood becoming incorporated during the crystallisation process.

Conclusions

Although the growth process was successful, the resulting material proved relatively weak and became brittle after drying. This brittleness suggests that the mineral composition contained a higher proportion of brucite than desired. This outcome may have been caused by insufficient control over the electrical current during the experiment, which may have exceeded the optimal values for promoting aragonite crystallisation.

Aquarium

III. Shell Structure



Hypothesis

Biorock consiststing primarily of calcium carbonate, the main component of seashells, imitating natural shell structures could allow the material to perform more efficiently, potentially achieving greater strength with less material.

Design

Another experiment explored a structure inspired by organic forms, specifically the geometry of seashells. The aim was to recreate the structural logic of a seashell using steel wire. The structure consisted of a cone-shaped form arranged around a central axis. To provide additional stability, a thin profiled steel ribbon was placed around the cone.

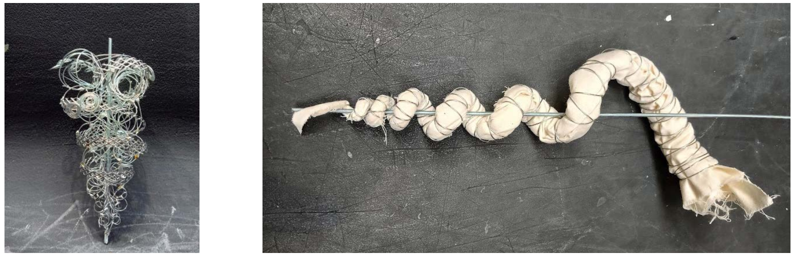
Conclusions

Initial observations of the Biorock growth revealed differences depending on the surface configuration. The structure consisted mainly of single steel wires combined with the profiled steel ribbon. During the first weeks of growth, significant material accumulation was observed on the profiled steel surface, while comparatively less growth occurred on the single steel wires. It was also observed that areas where wires were positioned closer together showed increased material deposition.

These observations further support the idea that surface complexity and proximity between structural elements promote stronger Biorock growth.

Sea

Structure design



24h in aquarium

3 weeks in the sea

6 weeks in the sea

10 weeks in the sea

III. Shell Structure

Final 16 weeks result

IV. Column

Hypothesis

This experiment explored whether steel wires could be shaped using a moulding method without permanently fixing the individual wires together. Through the growth of Biorock, the mould could potentially be removed, leaving behind a mineralised structural element.

Design

To test this hypothesis, a wooden structure was used as a mould to shape steel wires into a column form. Most of the wires consisted of two strands entangled together to promote material growth. Only at the base of the column was a single wire used to connect the different elements of the structure.

Conclusions

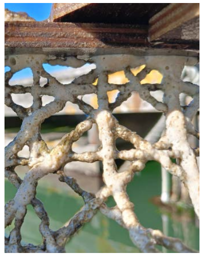
Initial observations again showed a clear difference in growth rate between single and entangled steel wires. Greater material accumulation was also observed at the points where wires intersected or came into contact with each other. These observations suggest that Biorock may be capable of mineralising and strengthening the connections between steel elements, potentially creating stable structural joints once the mould is removed.

Sea

Structure design

3 weeks in the sea

6 weeks in the sea



10 weeks in the sea

IV. Column

Final 16 weeks result

V. Arch

Hypothesis

Because Biorock primarily performs well in compression, it is relevant to investigate its potential application in portal structures in addition to column elements. For this purpose, a lightweight steel portal frame was designed.

In addition to the structural elements, several decorative components were incorporated in order to explore the aesthetic potential of the material alongside its structural characteristics.

Design

For the construction of the prototype, the different elements—made from entangled steel wires, were welded together. Due to the lightweight design and the relatively weak connections between elements, the resulting structure was intentionally fragile. This allowed the influence of the Biorock growth on the structural stability of the frame to be more clearly observed and evaluated.

Conclusions

Similar to the other experiments, the portal structure showed significant mineral growth around the intersections of the steel wires. Because these connections were intentionally designed to be weak, the initially unstable structure became structurally rigid through mineral accretion.

Unlike the column experiment, the absence of formwork reduced material use but also weakened the shape retention of the lightweight steel framework. The resting shape of the structure became fixed through mineral accretion, although this did not fully correspond to the intended optimal geometry of the portal. For very lightweight steel systems, it may therefore be preferable to use formwork to define the desired structural shape. Such formwork should be made from a non-conductive and water-resistant material, and as a reusable module in order to minimize waste.

The final result of the experiment was broken, probably due to activities in the port.

Sea

Structure design

3 weeks in the sea

6 weeks in the sea

6 weeks in the sea

VI. Wall System

Hypothesis

Because Biorock grows organically around a steel framework, placing the structure inside a mould could restrict its growth and provide greater control over the shaping of specific architectural details.

Using Biorock as a load-bearing structural system rather than as a solid material volume could reduce overall material use.

Combining a steel reinforcement system with fabric could create a strong and lightweight partition wall with efficient material use.

Design

This experiment was designed as a wall detail to test two moulding techniques, using wood and foam on either side of the structure. The surface of the wall consisted of steel wire braided into a piece of fabric. Two similar surfaces were placed parallel to each other, separated by a cavity intended to provide space for insulation.

Conclusions

Similar to previous experiments, the growth rate appeared to be greater in areas where steel wires were entangled or intersected. The combination of steel wire and fabric also provided strong adhesion for the growing material. Biorock was observed to grow through the fabric, effectively binding the different materials together.

The resulting material appeared less brittle than in previous experiments and showed a more unified structure rather than a composition of separate layers. This may be explained by the presence of the fabric within the structure, although it could also be related to a lower electrical current during the growth process.

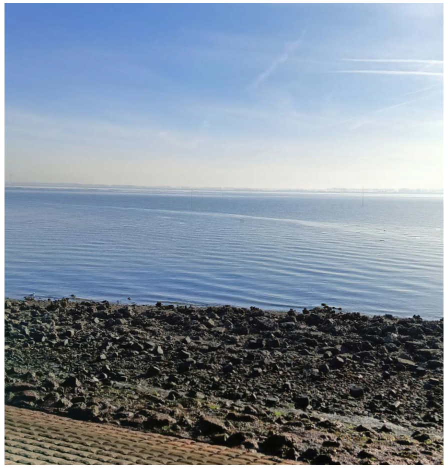
Aquarium

Structure design

24h

96h

144h



Appendix IV

Location Analysis

Dutch protected nature areas and its marine research and educational centers

(Own map)

Salinity of water bodies in Zeeland

(Own map)

Water depth in the Oosterschelde

(Own map)

🟧 Partially dry

⬛ -44 m

⬛ -35 m

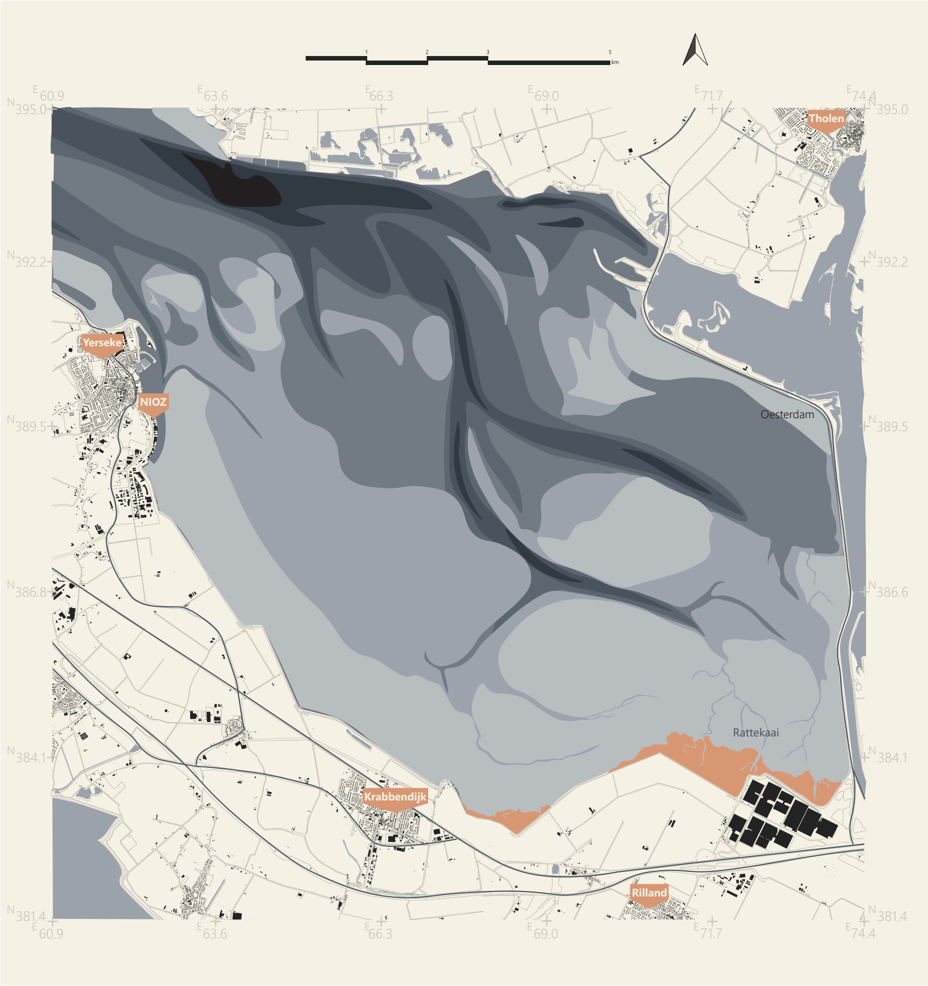
⬛ -25 m

▨ -15 m

▨ -5 m

▘▔▝ Existing buildings

Location analysis Yerseke-Rattekaai



(Own map)

🟧 Salt Marshes

⬛ -44 m

⬛ -35 m

⬛ -25 m

⬛ -15 m

⬛ -5 m

▨ 50-80% of the time dry

▨ >80% of the time dry

— Important road

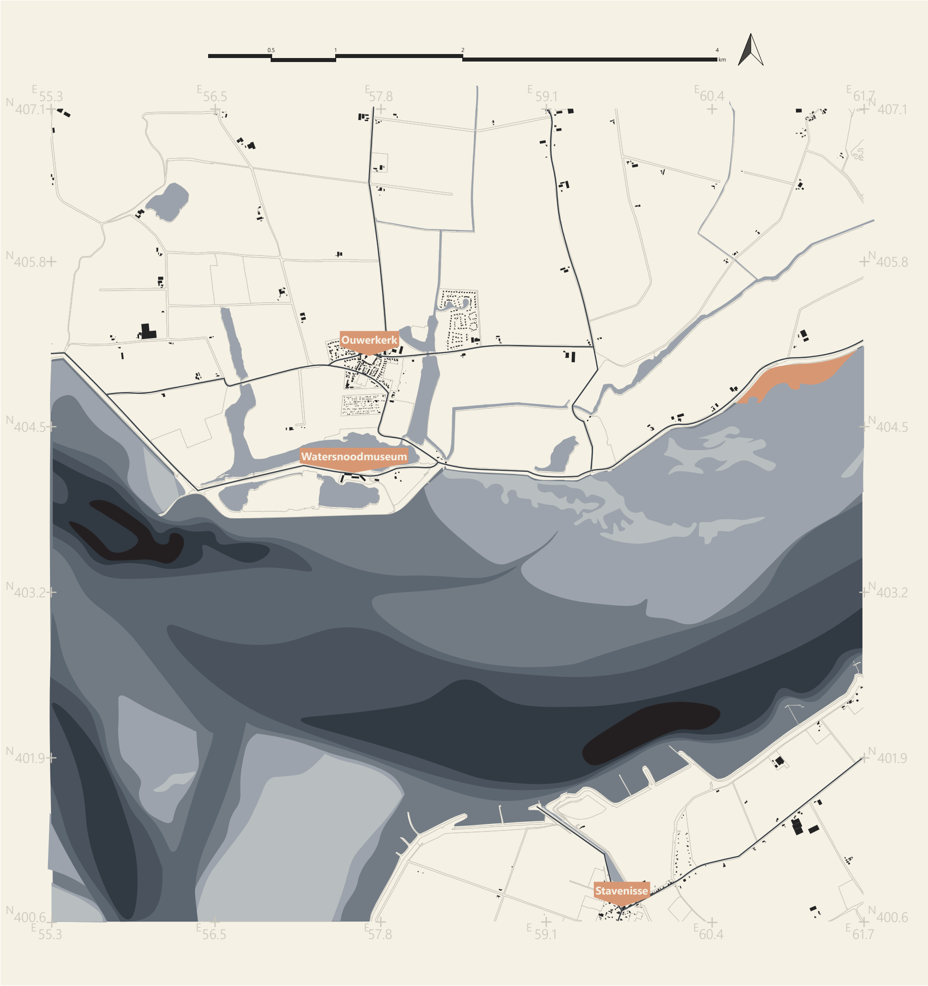
▘▔▝ Existing buildings

Location analysis Sint-Annaland

■ Salt Marshes
■ -44 m
■ -35 m
■ -25 m
■ -15 m
■ -5 m
■ 50-80% of the time dry
■ >80% of the time dry
— Important road
▪ Existing buildings

(Own map)

Location analysis Watersnoodmuseum surroundings

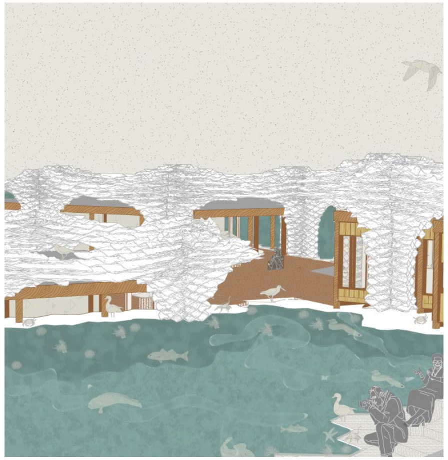


■ Salt Marshes
■ -44 m
■ -35 m
■ -25 m
■ -15 m
■ -5 m
■ 50-80% of the time dry
■ >80% of the time dry
— Important road
▪ Existing buildings

(Own map)

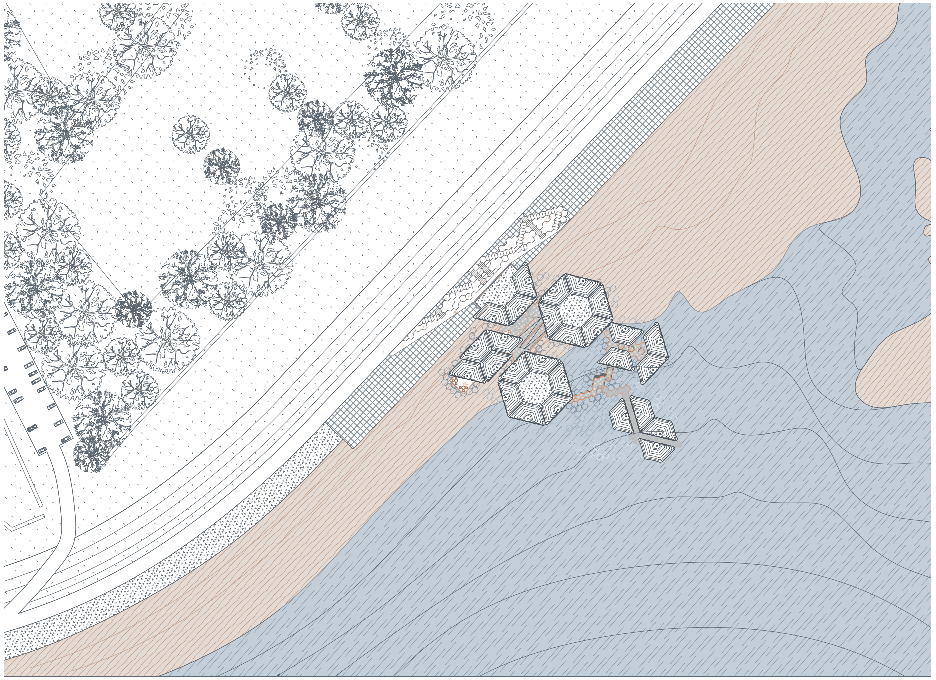
Locating the project and analysis of its surroundings

(Own map)

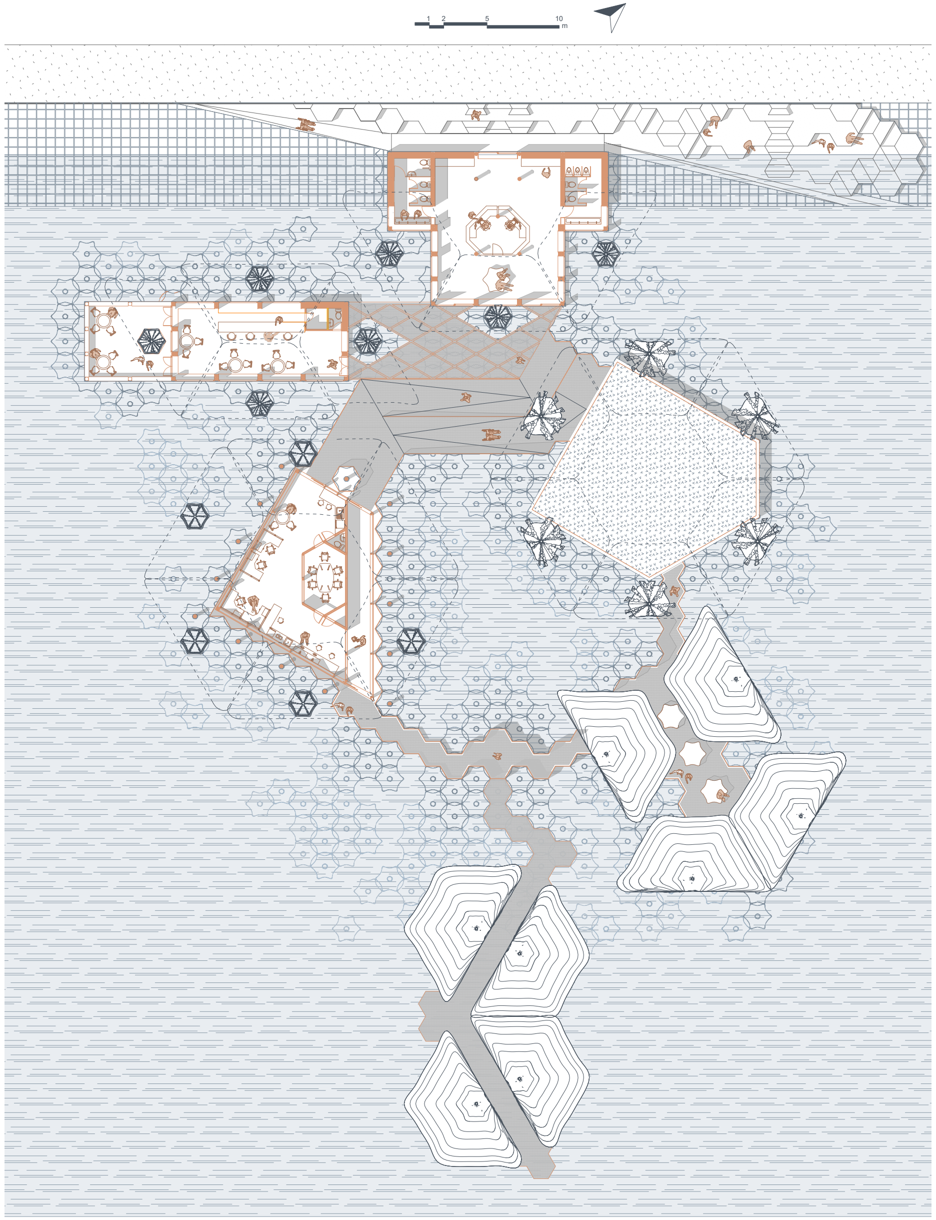


Appendix V

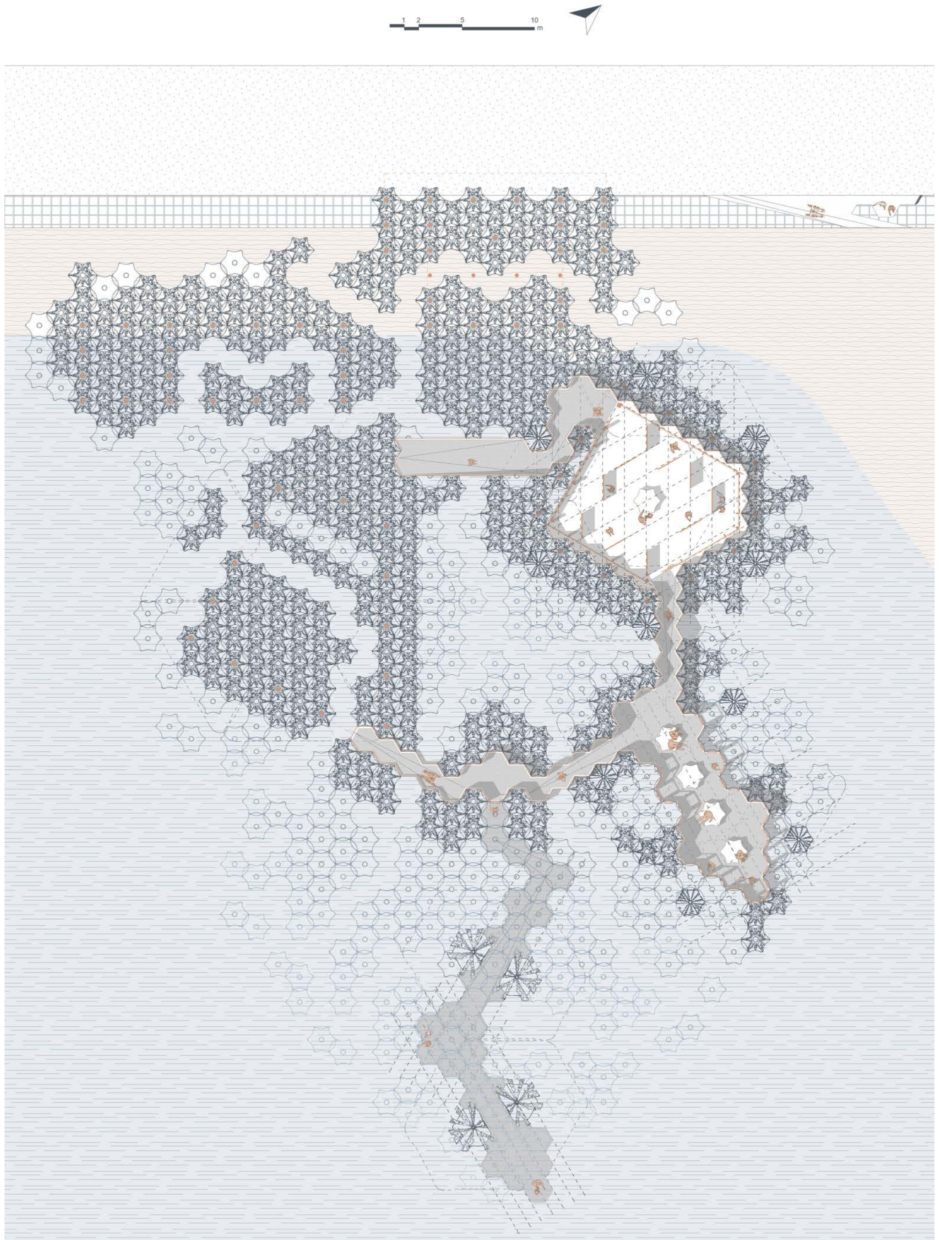
Achitectural Design



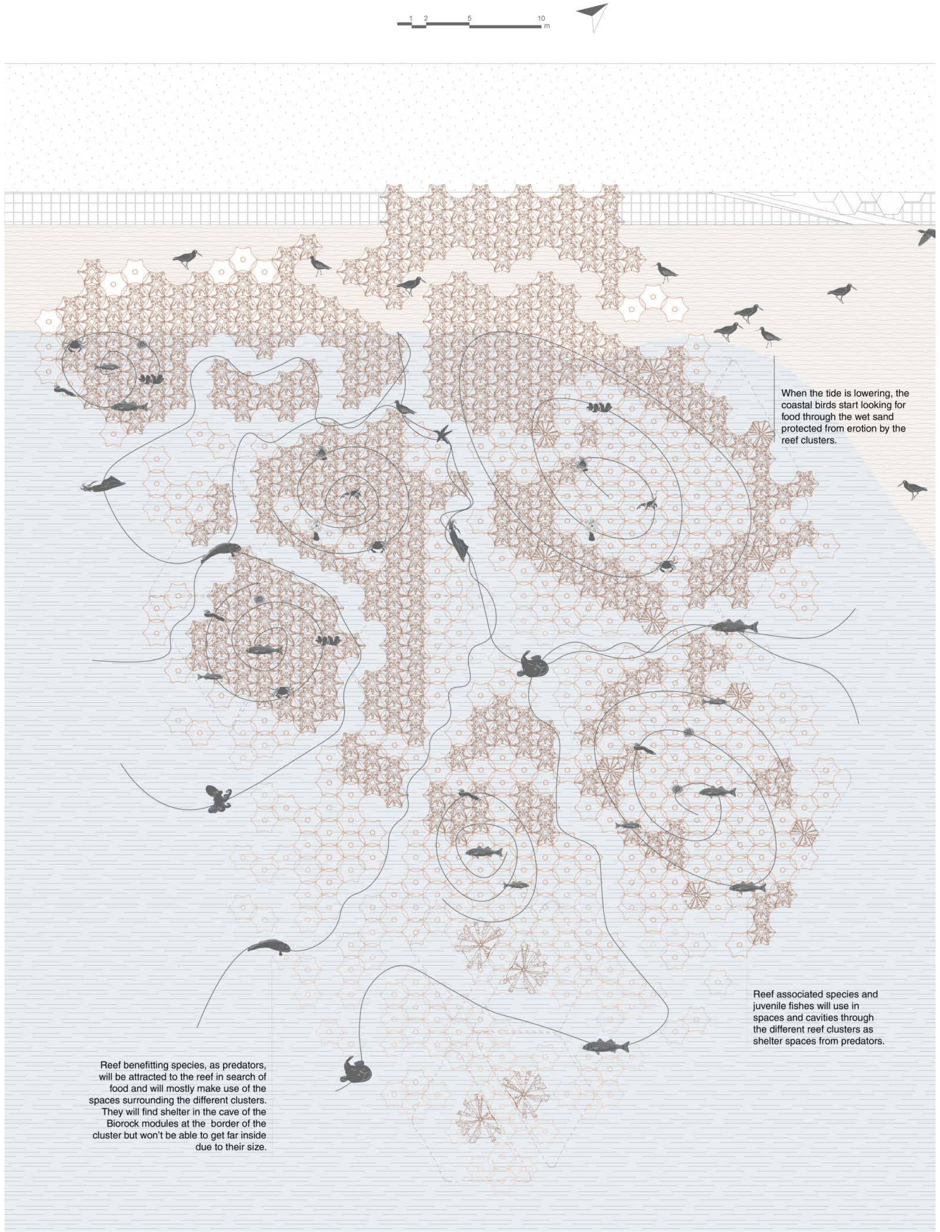
Situation drawing plan



Floorplan of the higher pavilions at high tide



Floorplan of the lower pavilions in-between tides

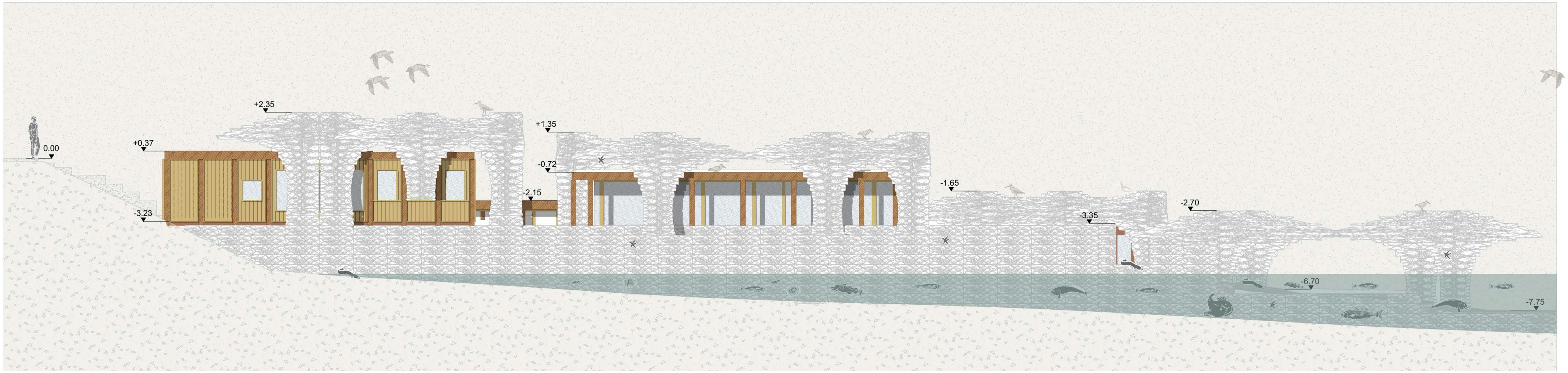


When the tide is lowering, the coastal birds start looking for food through the wet sand protected from erotion by the reef clusters.

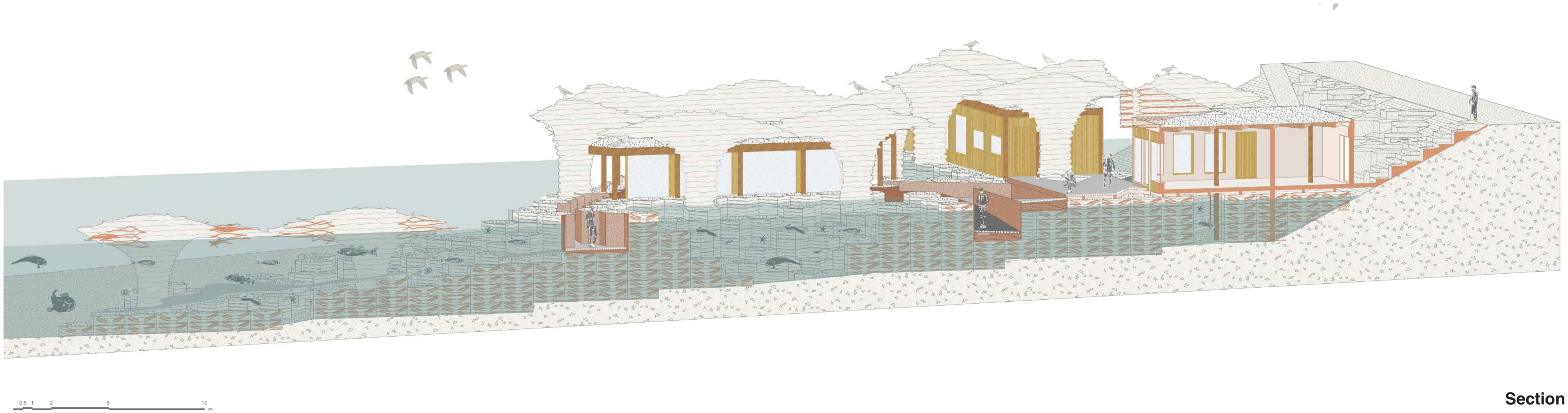
Reef associated species and juvenile fishes will use in spaces and cavities through the different reef clusters as shelter spaces from predators.

Reef benefitting species, as predators, will be attracted to the reef in search of food and will mostly make use of the spaces surrounding the different clusters. They will find shelter in the cave of the Biorock modules at the border of the cluster but won't be able to get far inside due to their size.

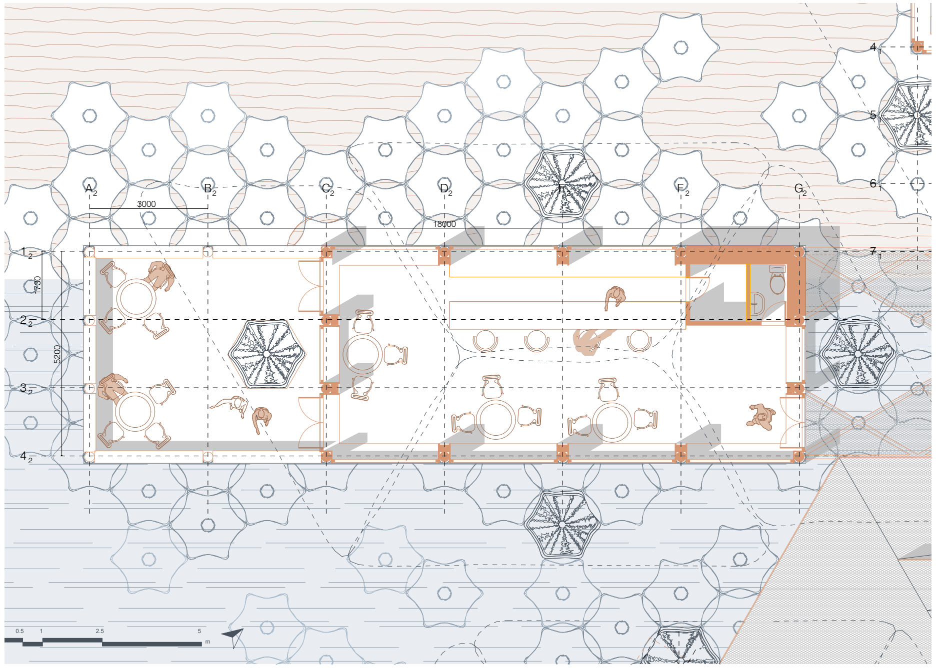
Floorplan of the ecological reefs in-between tides



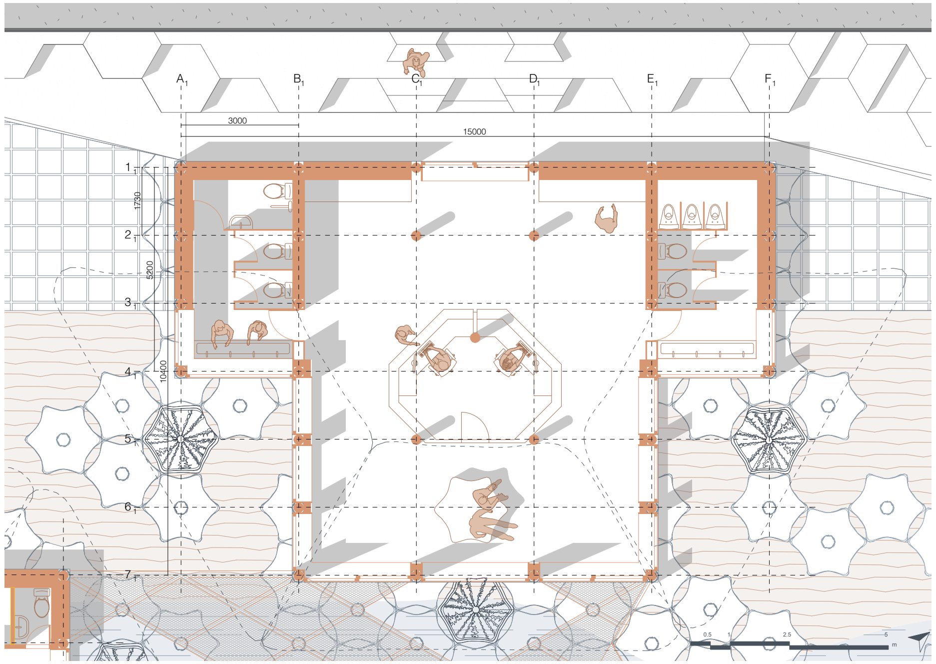
South West Elevation



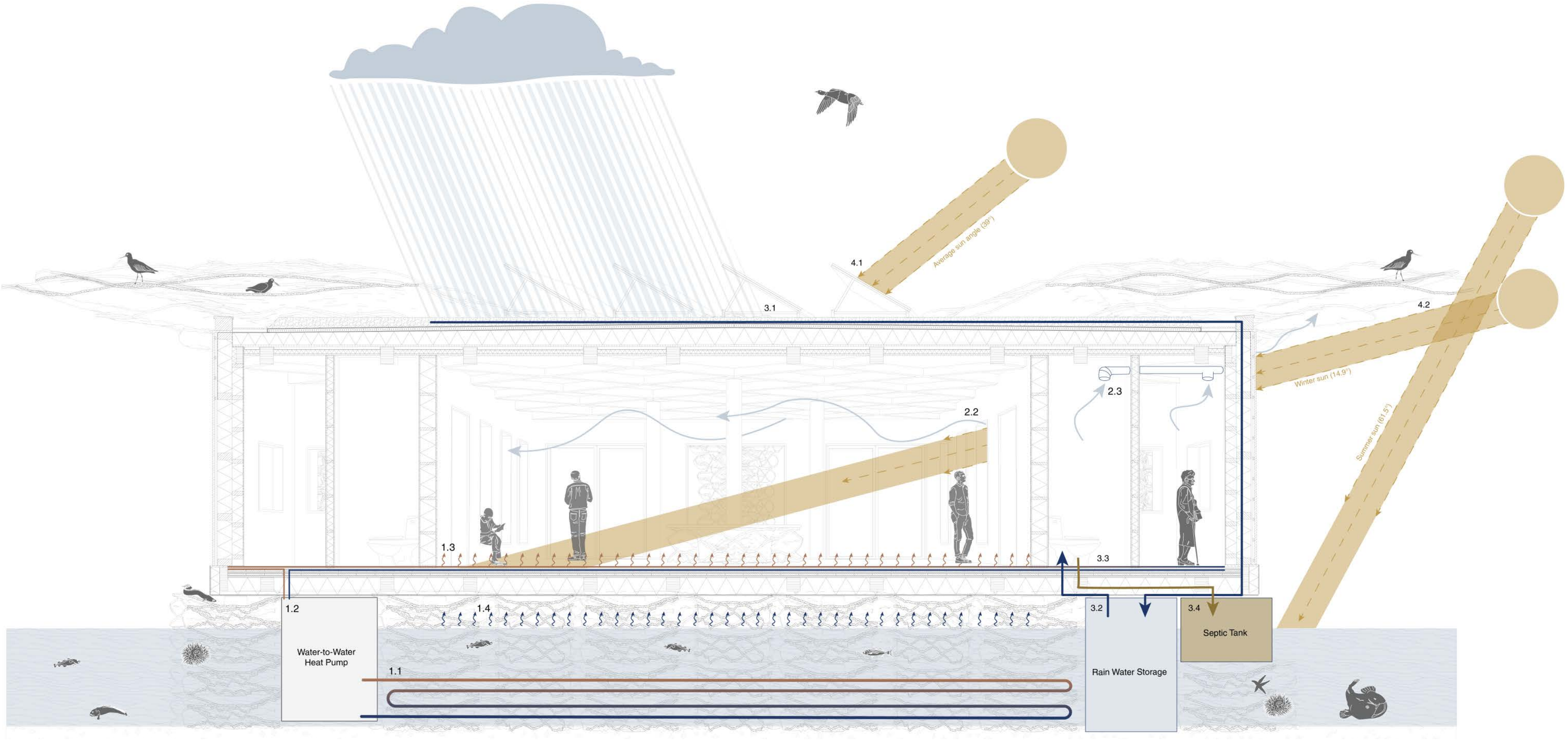
Section



Floorplan of the Restauration pavilion



Floorplan of the Entrance pavilion



1. Closed-loop Water-to-Water Heat Pump system

1.1 A closed pipe loop is submerged in the seawater.
1.2 The heat pump extracts thermal energy from the seawater.
1.3 Heat is distributed indoors through the floor heating system.

1.4 The water beneath the building remains cooler than the ambient air in summer and warmer in winter, helping to moderate indoor temperatures.

In summer, the system operates in reverse, using the seawater as a cooling source

2. Ventilation principles

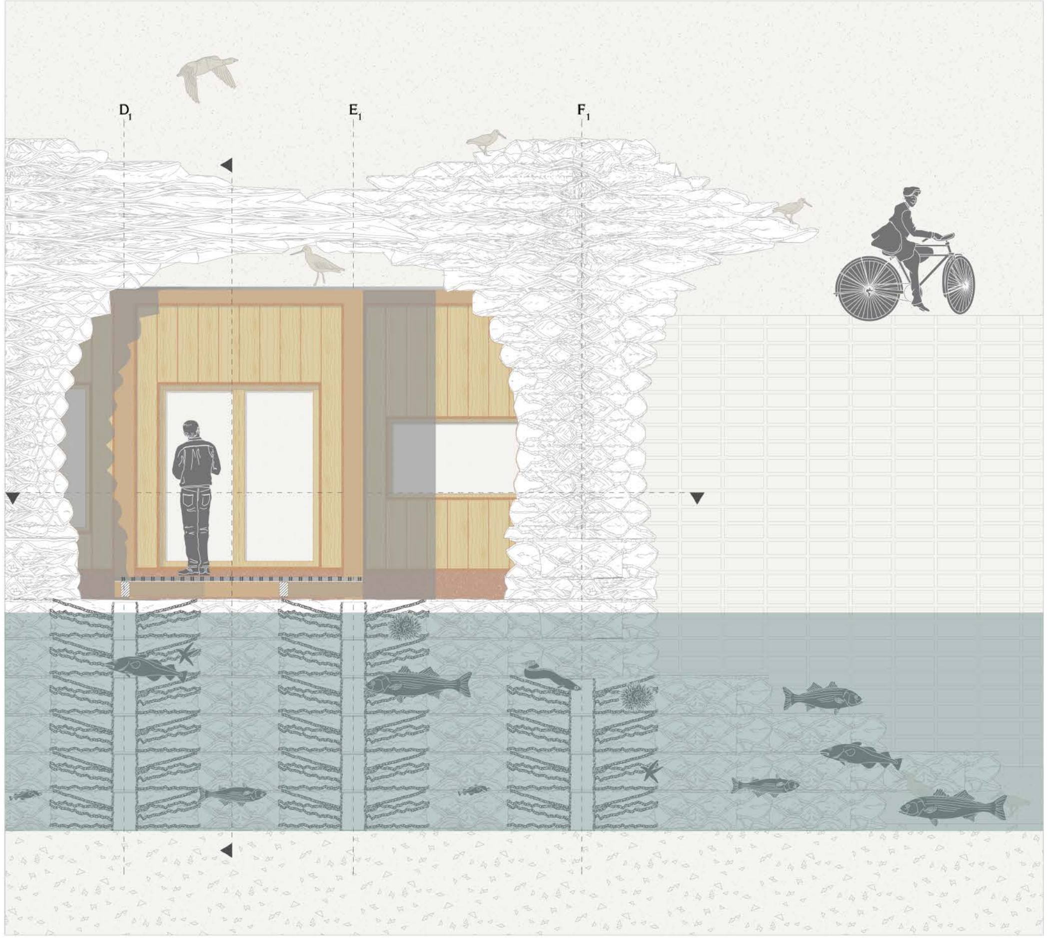
2.1 Air flowing above the water surface naturally cools the space.
2.2 The main areas of the building are naturally ventilated through operable windows and doors.
2.3 Bathrooms are mechanically ventilated using small extractor fans.

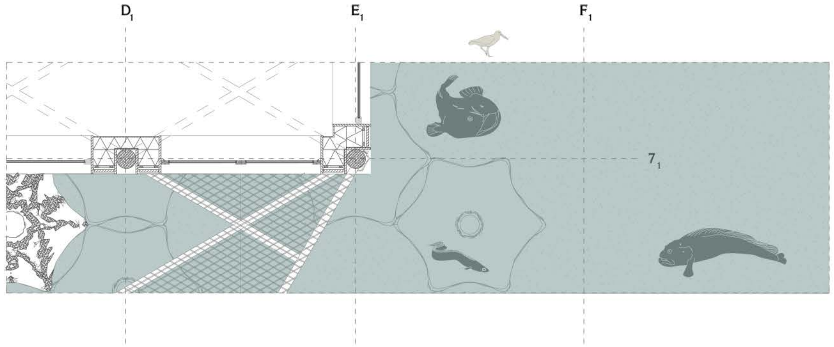
3. Rainwater Management

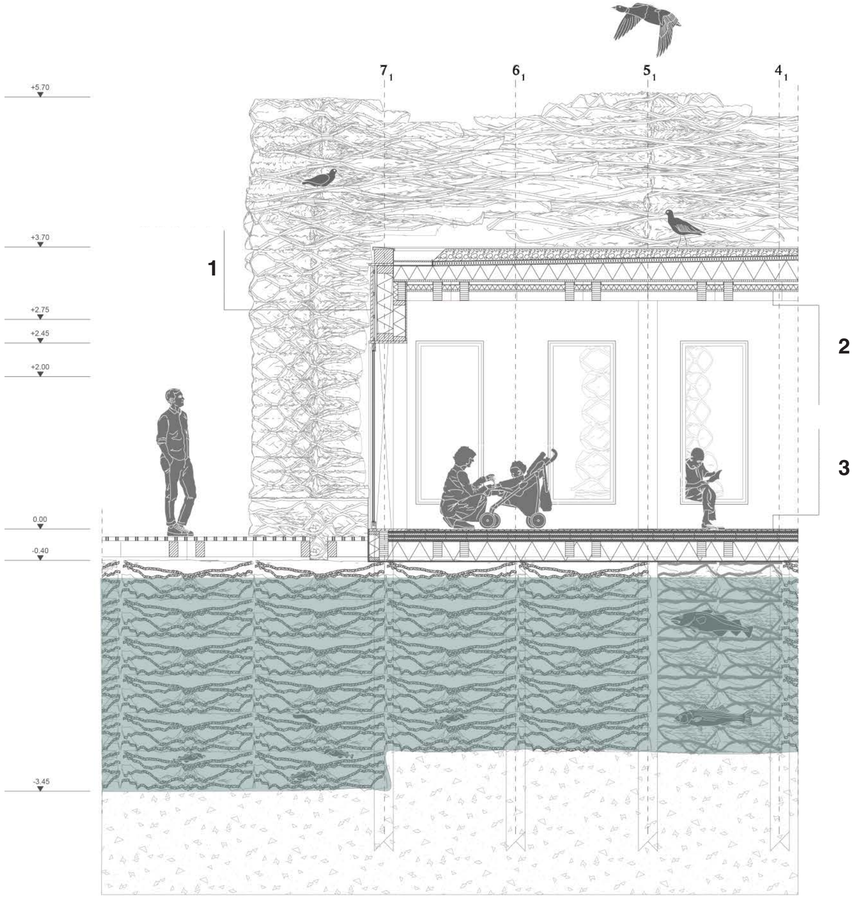
3.1 Rainwater is collected from the roof and directed to gutters along its edges.
3.2 The water is stored in a tank located within the reef beneath the building, in an easily accessible location.
3.3 Stored rainwater is reused for toilet flushing.
3.4 Wastewater from the toilets is directed to a septic tank positioned beneath the building at the edge of the reef, allowing easy access for maintenance and emptying.

4. Solar Energy

4.1 Solar panels are installed on the roof to generate the building's electrical energy.
4.2 The Biorock columns surrounding the building provide shading from direct solar radiation during summer, while still allowing lower winter sunlight to penetrate through the windows.







1

Modular Biorock column
25 mm Wooden cladding
24 mm battens
24 mm counterbattens
Facade membrane
215/100 mm wood blocking inlaid wool insulation
160/60 mm wood blocking inlaid wool insulation
Vapour barrier
15 mm gypsum board cladding

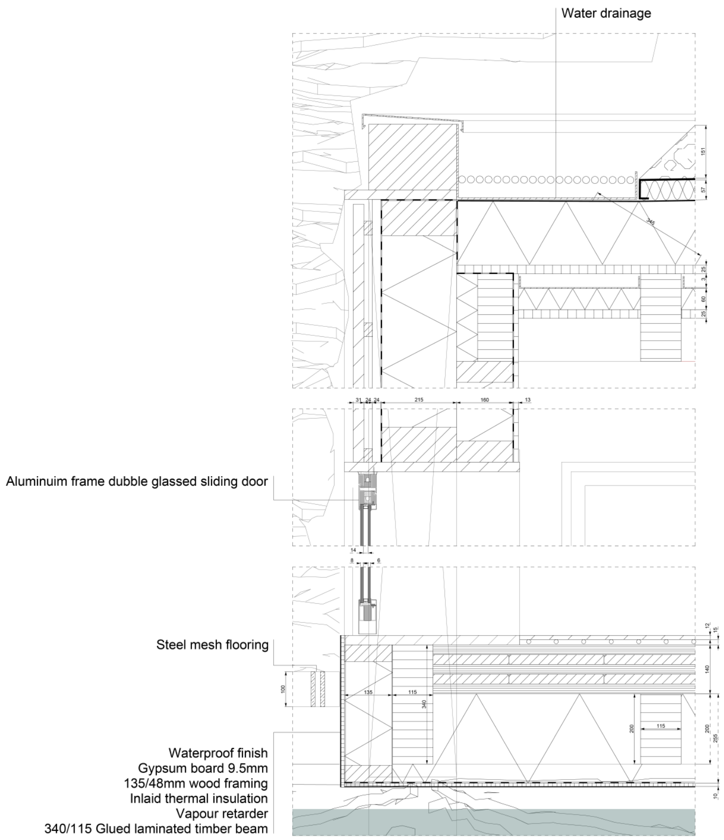
2

190 mm shell substrate
Filter fleece
60 mm drainage element
Protective fleece
Roof proof sealant
190-150 mm PIR rigid foam insulation
Vapour Barrier
25mm OSB
115/250mm Glulam beam
Aluminium angle framing between beams
Acoustic element: 60mm wool insulation
+ 25 mm wood lightweight panel

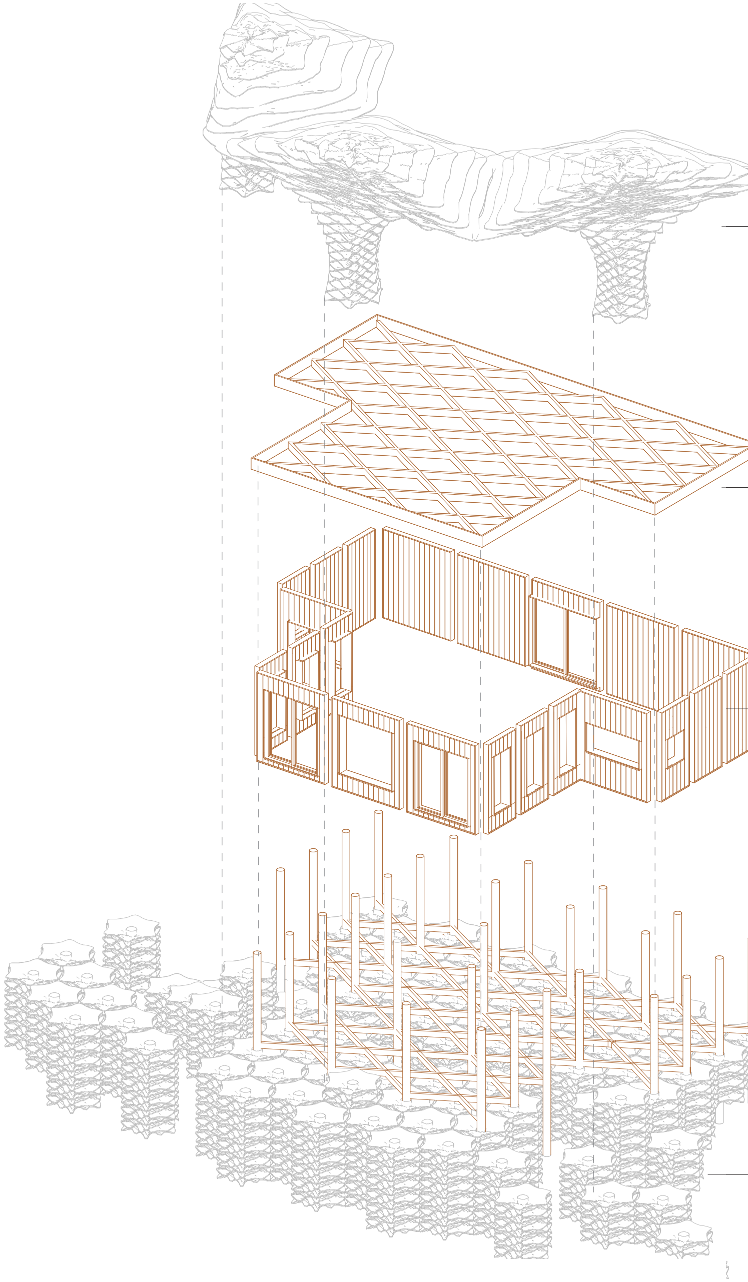
3

Wooden flooring 12mm
Floor heating mat 15mm
Cross laminated timber 140mm
200/115mm Glued laminated timber beams
Inlaid thermal insulation
Gypsum board 9.5mm
Waterproof finish
Modular Biorock foundation elements 500mm

1:20 fragment of the entrance pavilion



1:5 detail of the entrance pavilion



1. Modular Biorock column structures

The structures offer a sun protection to the facade of the building oriented to the south in the summer while offering a habitat and nesting space for coastal species.

2. Diagonal Glulam roof structure

Based on the reef grid structure the roof structure is composed of 115/250 mm glulam beams in two diagonal direction. The beams are partially visible from the indoor space

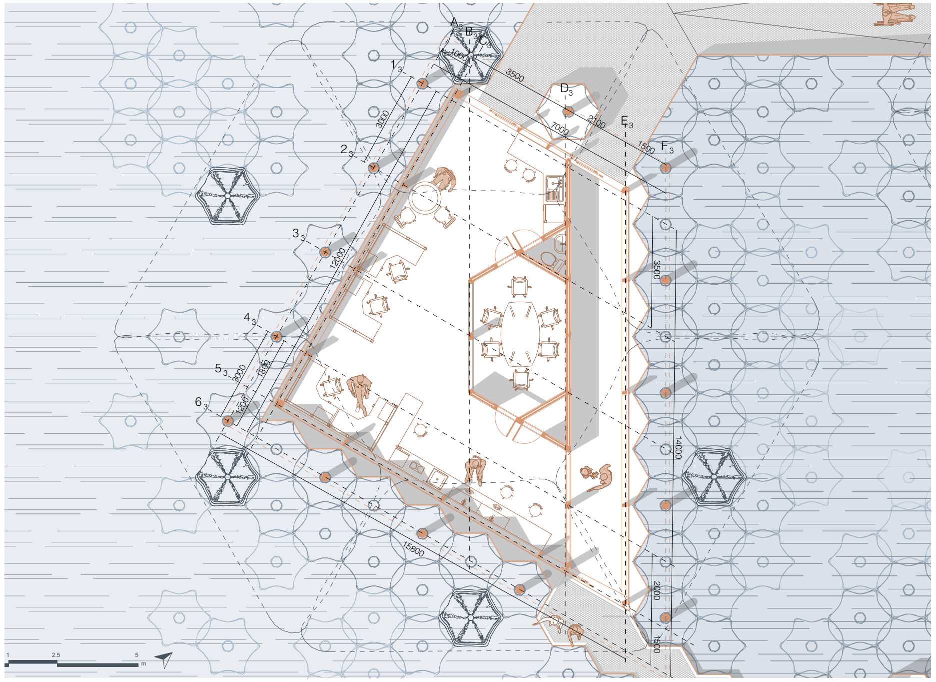
3. Wooden facade panels

Inbetween the columns modular wooden panels are fixed. Those are provided with a base insulation layer and a second layer with the indoor wall finish.
The closed panels are dimensionally stable and their placement in three different direction ensures the stability of the whole structure.

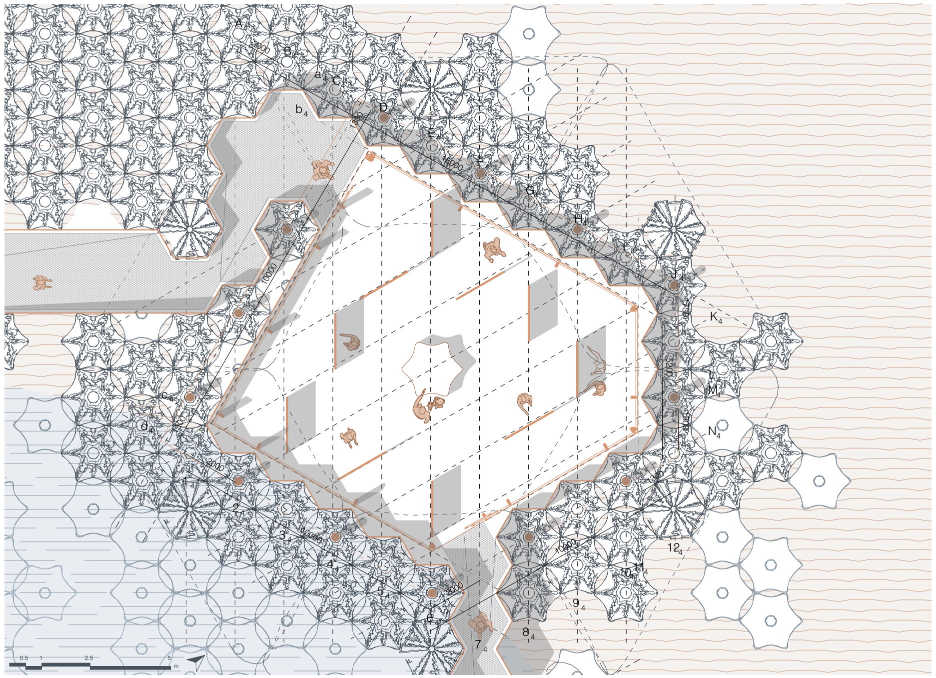
4. Wooden foundation and column

The timber foundation piles extend into columns within the façade and interior spaces. Those are "fossilized" in the sea water with Biorock growing withing the porous material. A diagonal 115/200 mm glulam beam structure is connected between the timber piles as base for the floor construction.

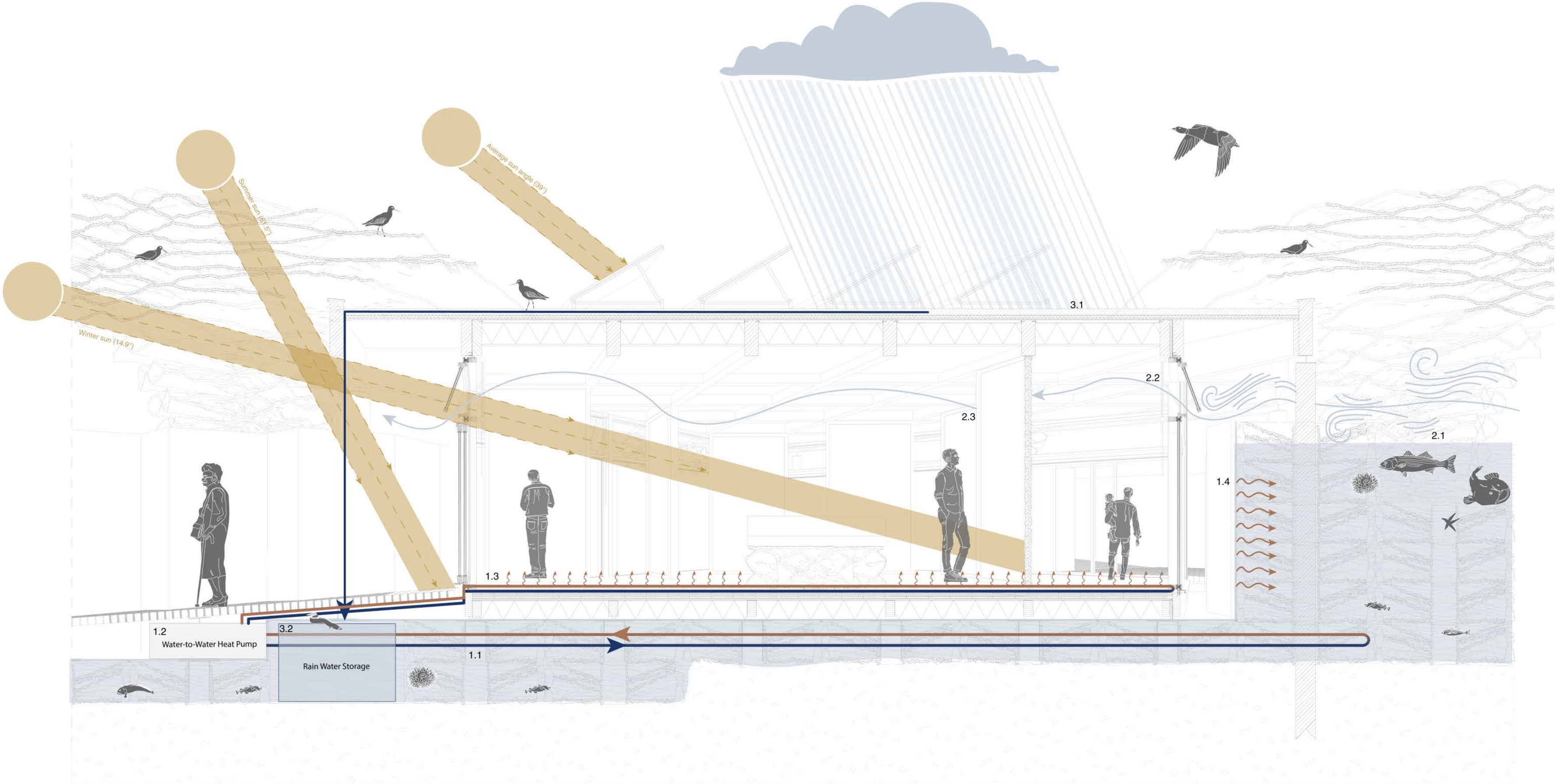
Construction axonometry of the entrance pavilion



Floorplan of the Reasearch center pavilion



Floorplan of the Exhibition pavilion



1. Closed-loop Water-to-Water Heat Pump system

1.1 A Closed pipe loop is submerged in the sea water.
1.2 Heat pump extracts the heat from the sea water
1.3 The heat is transfered to the indoor spaces through a floor heating system

1.4 The water surrounding the building naturally regulates the indoor climate absorbing the heat in the warm summer days

In the summer the system is reversed, using the sea water as cooling source

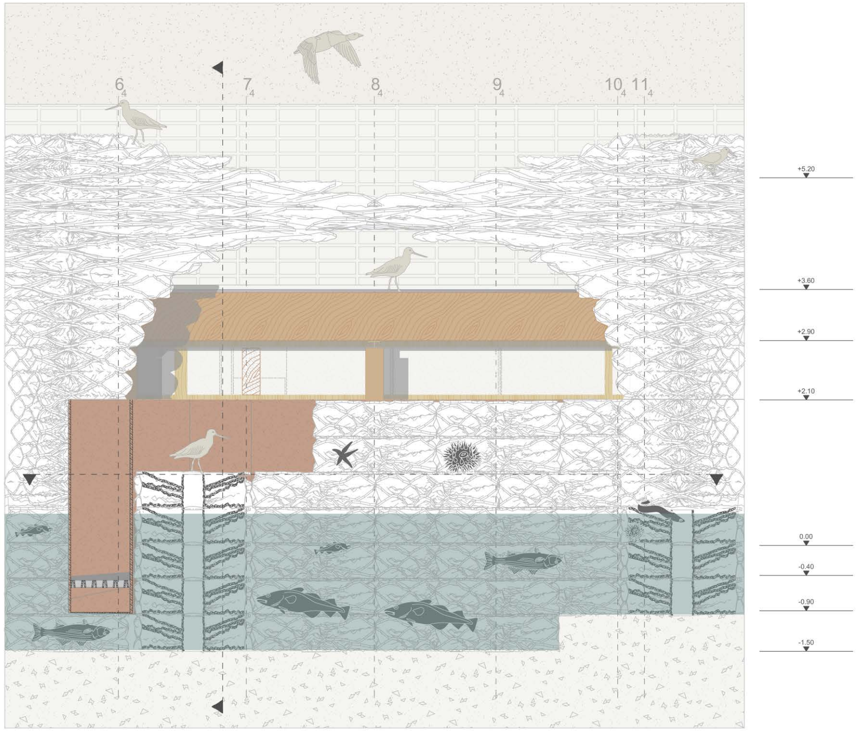
2. Ventilation principles

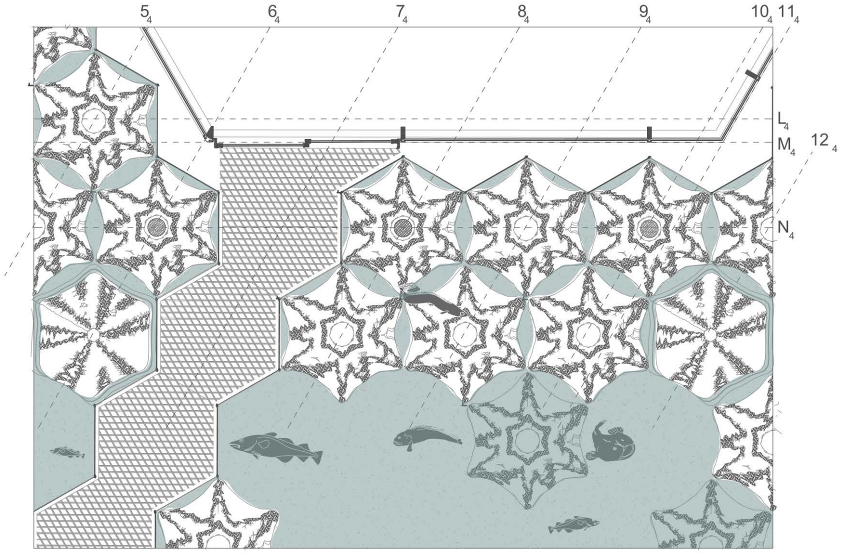
2.1 The air flows above the water surface, naturally cooling it
2.2 The whole building is naturally ventilated through manually openable windows.
2.3 The pavilion exists out of one open indoor space where the air can easily flow through

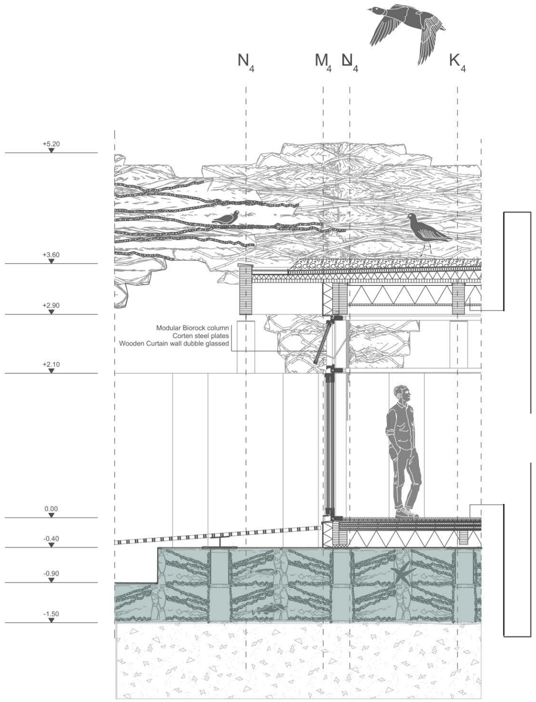
3. Rain Water

3.1 Rain water is collected on the roof and lead to gutters at the edge of it.
3.2 The water is stored in a tank placed in the reef under the building at the most accessible location.
3.3 The water is used for cleaning and toilet flushing.

Climate section of the Exhibition pavilion



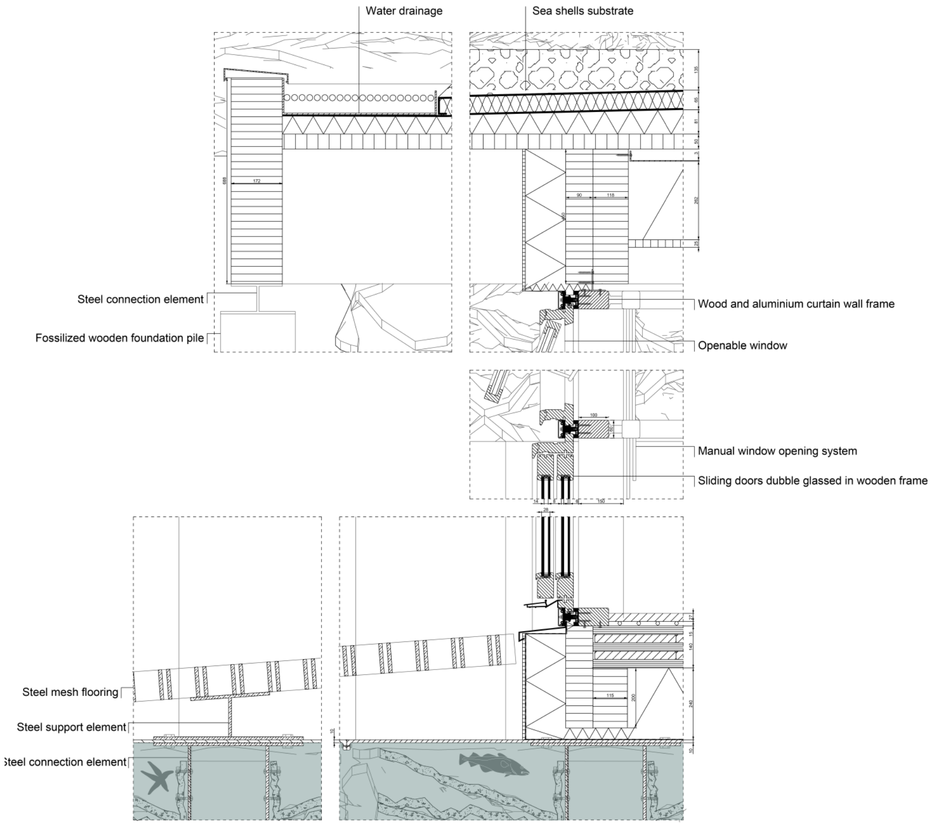




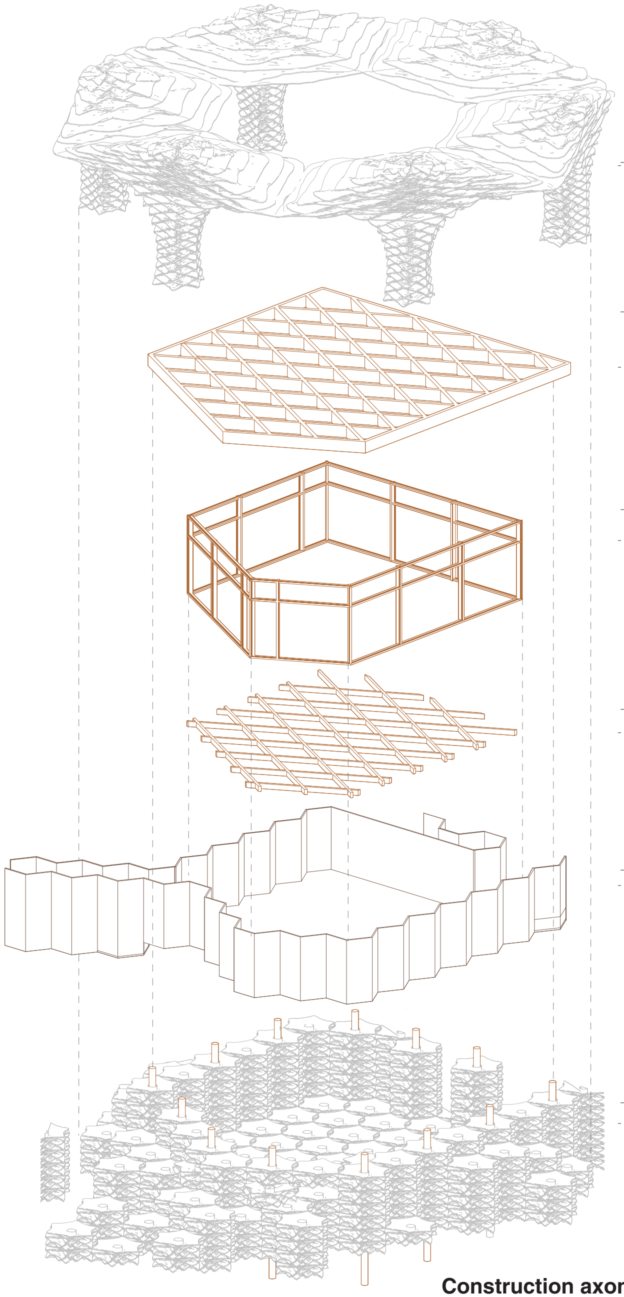
190 mm shell substrate
Filter fleece
60 mm drainage element
Protective fleece
Roof proof sealant
60-140 mm PIR rigid foam insulation
Vapour Barrier
25mm OSB
170/450mm Glulam beam
Aluminium angle framing between beams
Acoustic element: 260mm thermal insulation insulation
+ 25 mm wood lightweight panel

Wooden flooring 12mm
Floor heating mat 15mm
Cross laminated timber 140mm
115/200mm Glued laminated timber beams
Inlaid thermal insulation
Gypsum board 9.5mm
Waterproof finish
Modular Biorock foundation elements 500mm

1:20 fragment of the Exhibition pavilion



1:5 Detail of the Exhibition pavilion



1. Modular Biorock column structures

The Biorock columns are here used for both hosting coastal species in and above water and provide shading to the glassed facade of the structure.

2. Diagonal Glulam roof Structure

Based on the reef structure underneath the roof structure is composed of 170/450 mm Glulam beams in two diagonal direction.
The same height of beam is visible as in the entrance pavilion giving the same ceiling experience.

3. Curtain wall

Following the diagonal structure of the roof and floor the facade is fully glassed with a wood/aluminium curtain wall.
The vertical wooden elements have a section length of 150 mm and width of 60 mm. The horizontal elements have a section of 100/60 mm.

4. Diagonal Glulam floor structure

Based on the reef structure underneath the floor structure is composed of 115/200 mm Glulam beams in two diagonal direction.

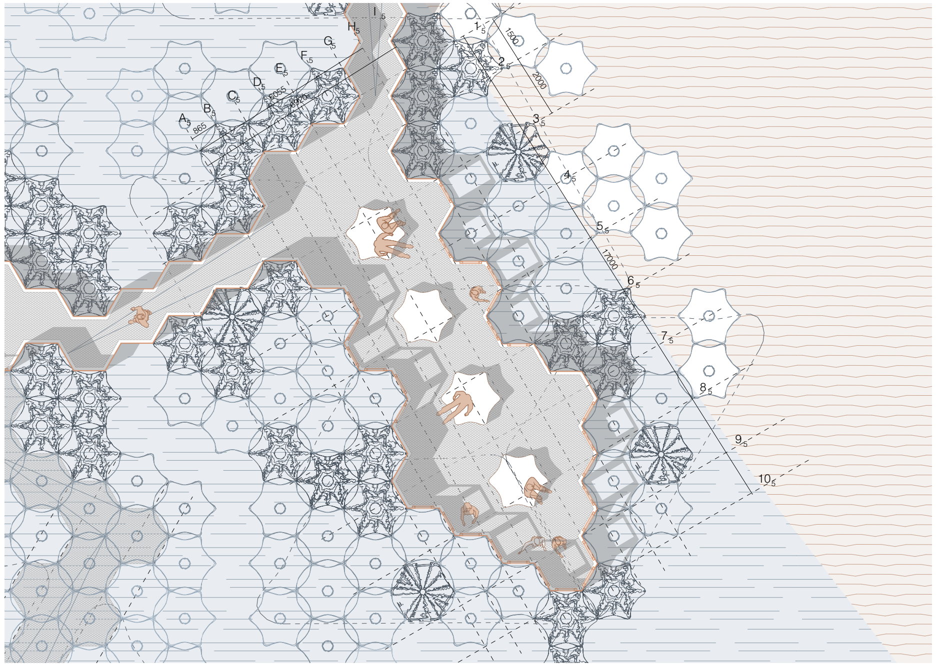
4. Modular Corten steel "boat" structure

The space is protected from water by a modular Corten steel structure inspired by sheet pile wall construction.

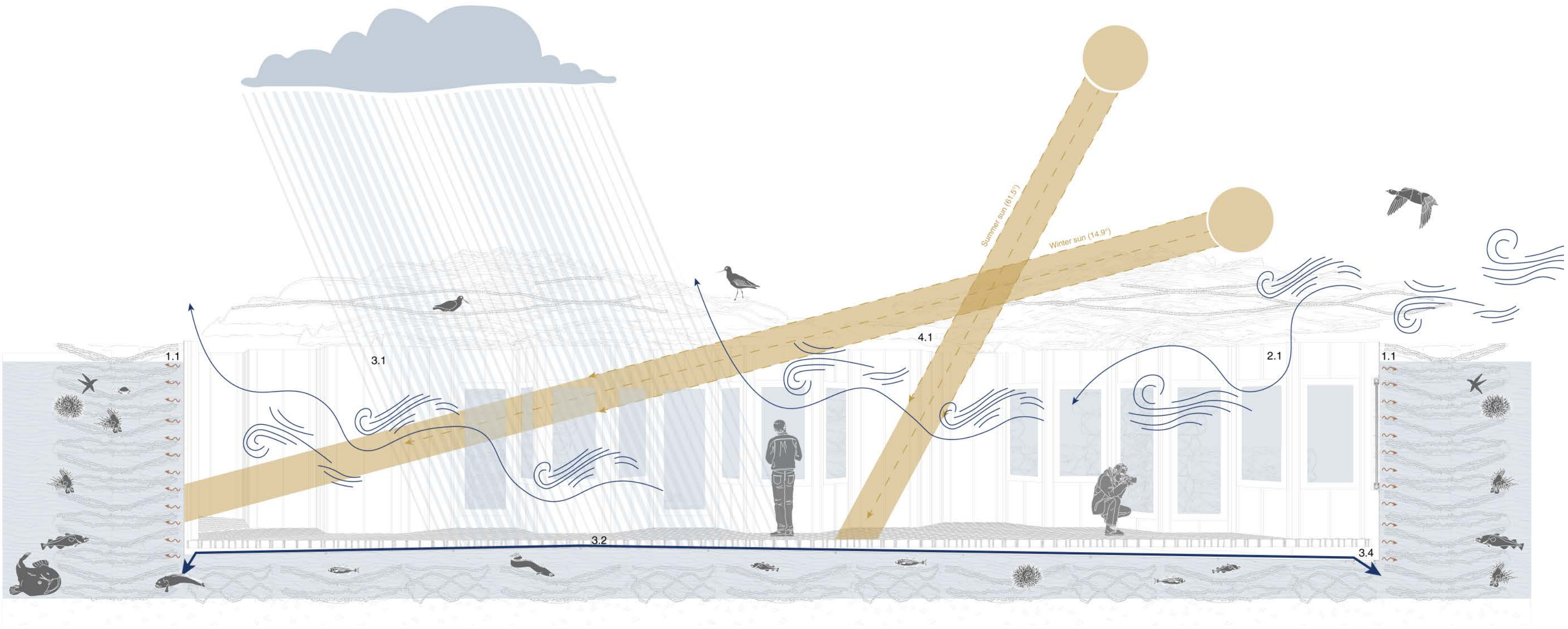
5. Modular Biorock foundation

The entire structure is supported by a Biorock reef construction, functioning as a platform that forms the base
Wooden foundation piles extend through a modular Biorock wall surrounding the entire structure ensuring the stability of the overall system.

Construction axonometry of the Exhibition pavilion



Floorplan of the Observatory pavilion



1. Indoor climate

1.1 The building is thought as an enclosed space within an unconditioned outdoor climate; temperature is there for unregulated and climate-dependent. The surrounding water acts as a heat sink for the steel structure during summer.

2. Ventilation principles

2.1 The space is fully open from the top creating an outdoor climate in the enclosed space. Ventilation is therefor not required, the airflow depending fully from the current wind conditions.

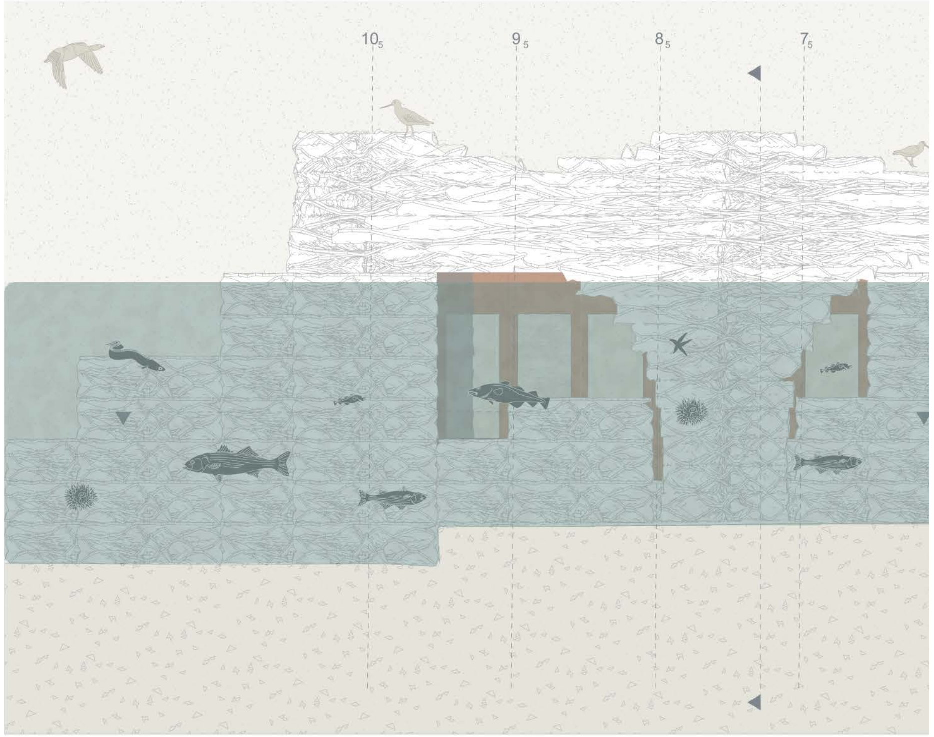
3. Rainwater Management

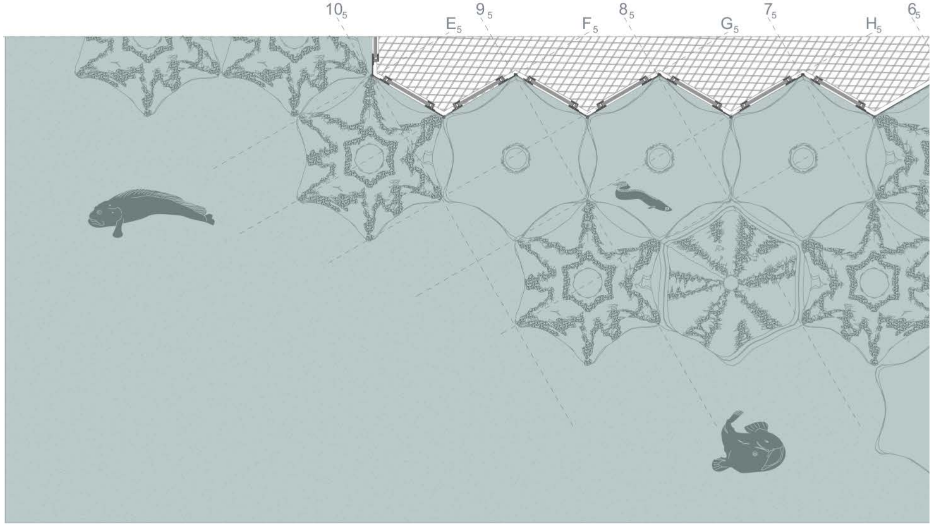
3.1 As the building does not have a conventional roof enclosure, rainwater is allowed to enter the space freely.
3.2 The water passes through the steel mesh floor system.
3.3 Angled Corten steel plates beneath the floor guide the rainwater toward the edges of the space, where it is collected and discharged.
3.4 The drainage system remains open during low tide and closes automatically under the pressure of the water during high tide.

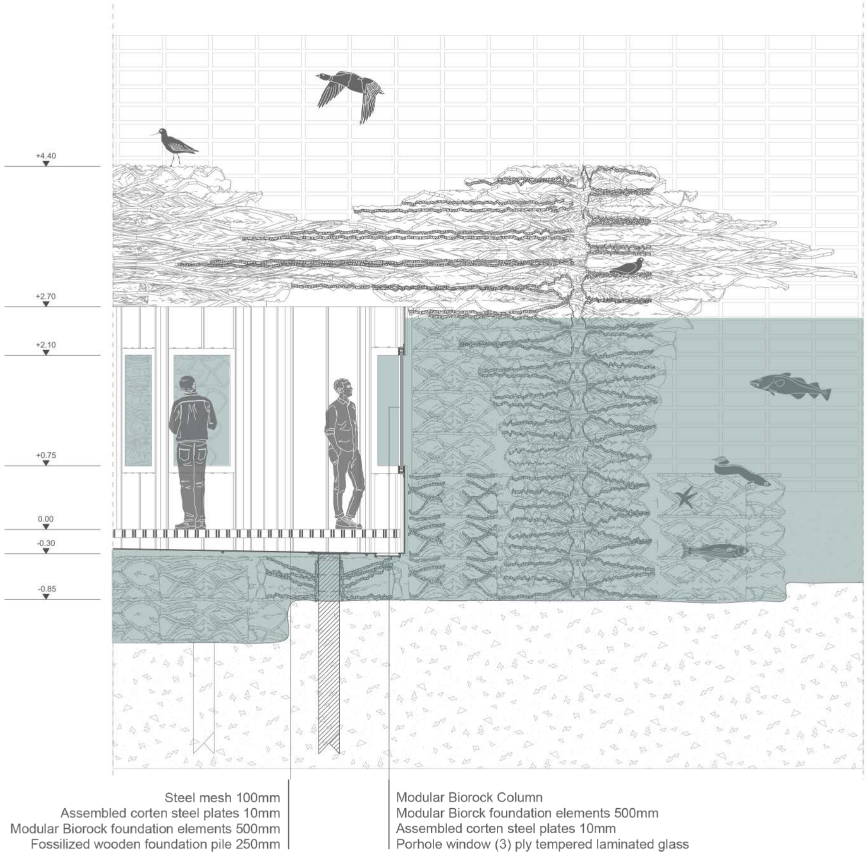
4. Solar Energy

4.1 The Biorock columns provide partial shadding in the space for protection in the summer
4.2. The organic and partially open structure of the columns offer a playfull experience of natural light evolving through the day and seasons.

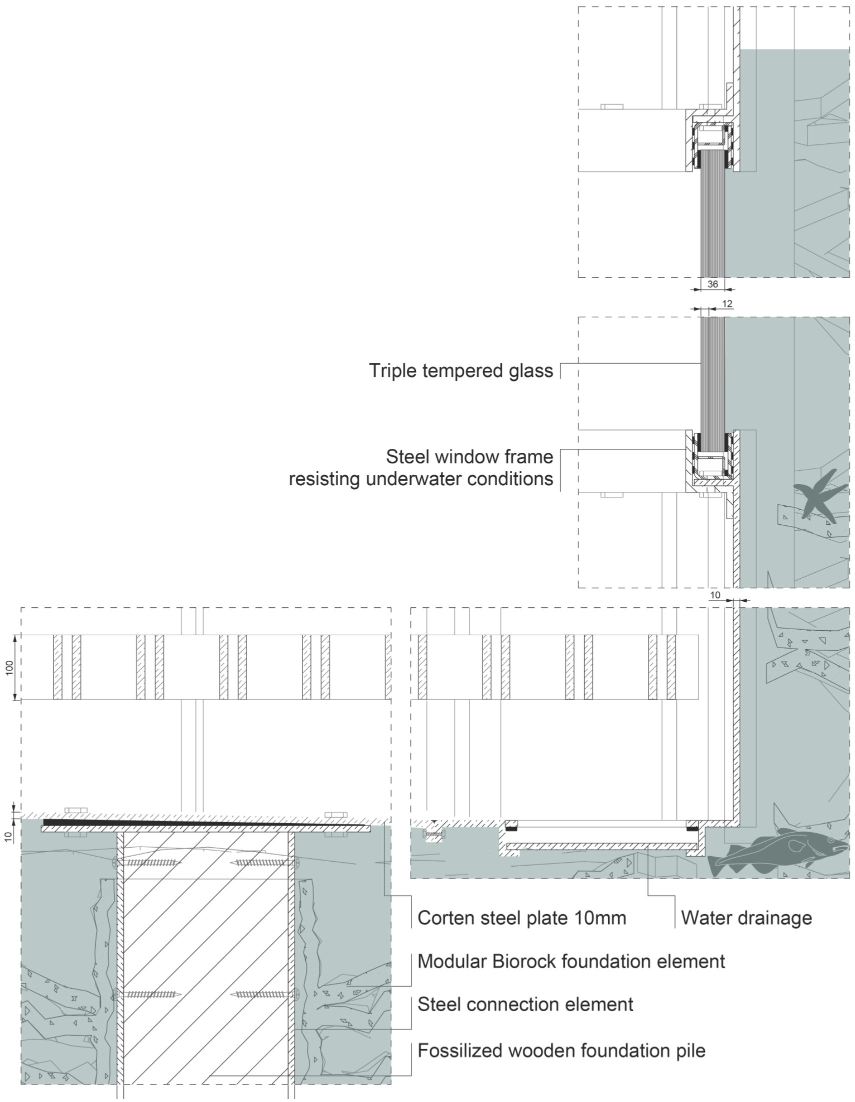
Climate section of the Observatory pavilion







1:20 fragment of the Observatory pavilion



Triple tempered glass

Steel window frame
resisting underwater conditions

Corten steel plate 10mm

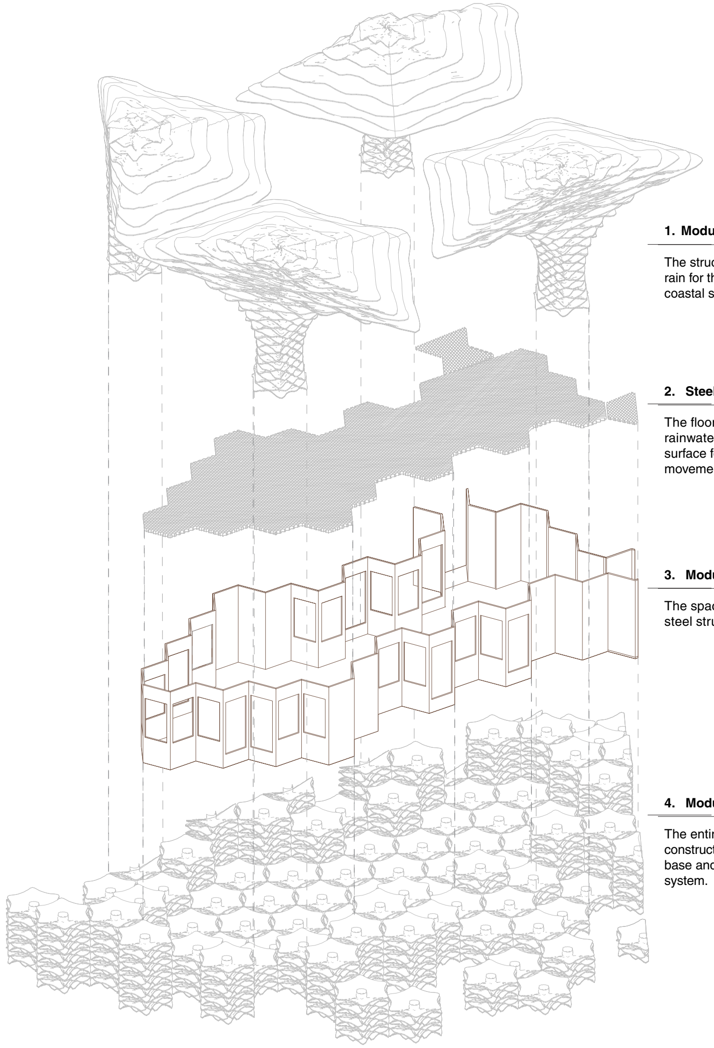
Water drainage

Modular Biorock foundation element

Steel connection element

Fossilized wooden foundation pile

1:5 Detail of the Observatory pavilion



1. Modular Biorock column structures

The structures offer a partial protection from the sun and rain for the visitors and habitat and nesting spaces for the coastal species.

2. Steel mesh floor

The floor is an elevated steel mesh surface, allowing rainwater to pass through while providing a dry, level surface for comfortable and accessible outdoor movement.

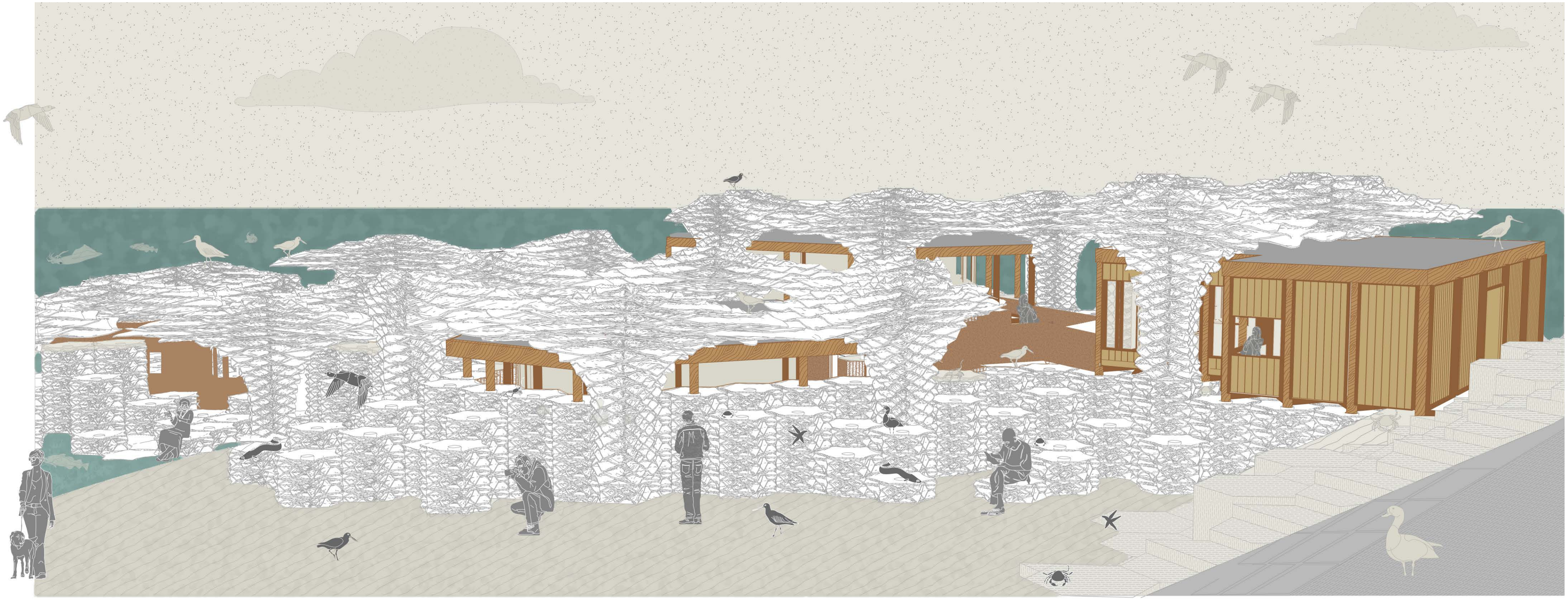
3. Modular corten steel “boat” structure

The space is protected from water by a modular Corten steel structure inspired by sheet pile wall construction.

4. Modular Biorock foundation

The entire structure is supported by a Biorock reef construction, functioning as a platform that forms the base and as peripheral elements that stabilise the overall system.

Construction axonometry of the Observatory pavilion



Ôde à la Mer

Biorock as a building tool for futur proof architecture contributing to its ecosystem