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2. Background and Related Work

This chapter reviews and compares several companies with relevant prior projects. The analysis focuses not only on their core concepts and features but also on the materials, sensor mechanics, and distinguishing factors such as biological and geographical analysis.

2.1 Introduction

This chapter establishes the technical and scientific foundation for the Maris Habitats project by situating it within the broader context of artificial reef design and underwater environmental monitoring. Traditional artificial reefs are usually passive structures that provide physical habitat support, while marine monitoring systems are often treated as separate technical equipment.

Maris Habitats aims to connect these two areas by combining modular reef infrastructure with a removable Smart Module. Instead of focusing on real-time data transmission, the system is designed for long-term local data logging. This approach reduces technical complexity and makes the concept more realistic for a low-power underwater system.

The chapter reviews artificial reef concepts, existing companies, material options, sensor placement challenges, and biological and geographical factors. This background helps justify the project direction: a modular Reef Block system supported by environmental data collection rather than a fully live underwater Internet of Things (IoT) platform.

2.2 Concepts

Artificial marine habitats can be designed in several ways to help restore marine ecosystems and support endangered fish species. One approach is the use of 3D-printed reef structures, which can be made from materials such as ceramic, limestone, or eco-concrete.

These materials are durable and suitable for marine environments. Examples of projects using this approach include Reef Design Lab in Australia, which develops 3D-printed reef structures for marine habitat restoration, and SECORE coral restoration projects, which focus on rebuilding damaged coral reefs by supporting coral growth and reef recovery **[1]**, **[2]**.

Figure 1 shows an example of a 3D-printed artificial reef structure. This type of design is relevant to Maris Habitats because it shows how repeated artificial structures can create habitat complexity underwater.

Figure 1: Example of a 3D-printed artificial reef structure used for marine habitat restoration **[3]**

Another commonly used solution is reef balls. These are concrete dome structures with holes that mimic natural reef caves. Because of their simple design, they are easy to mass-produce and very stable when placed on the seabed.

The holes and cavities provide immediate shelter for fish and other marine animals, allowing the structures to quickly function as protective habitats **[4]**, **[5]**.

Figure 2 presents an example of a reef ball structure. The holes in the concrete dome show how a simple shape can still provide sheltered spaces for marine life.

Figure 2: Example of reef ball structures used as artificial reef habitats **[6]**

A different method is the creation of Bio-Rock or electric reefs. These reefs consist of metal structures through which a small electrical current is passed. This current causes minerals from seawater to deposit onto the structure, gradually forming a limestone-like coating. Previous research showed that corals under biorock treatment had higher growth than the control group, with an observed growth ratio of 4:1 in the studied case. This technique is known as Bio-Rock technology **[7]**.

Figure 3 shows an example of a Biorock reef structure that has been colonized by coral after installation.

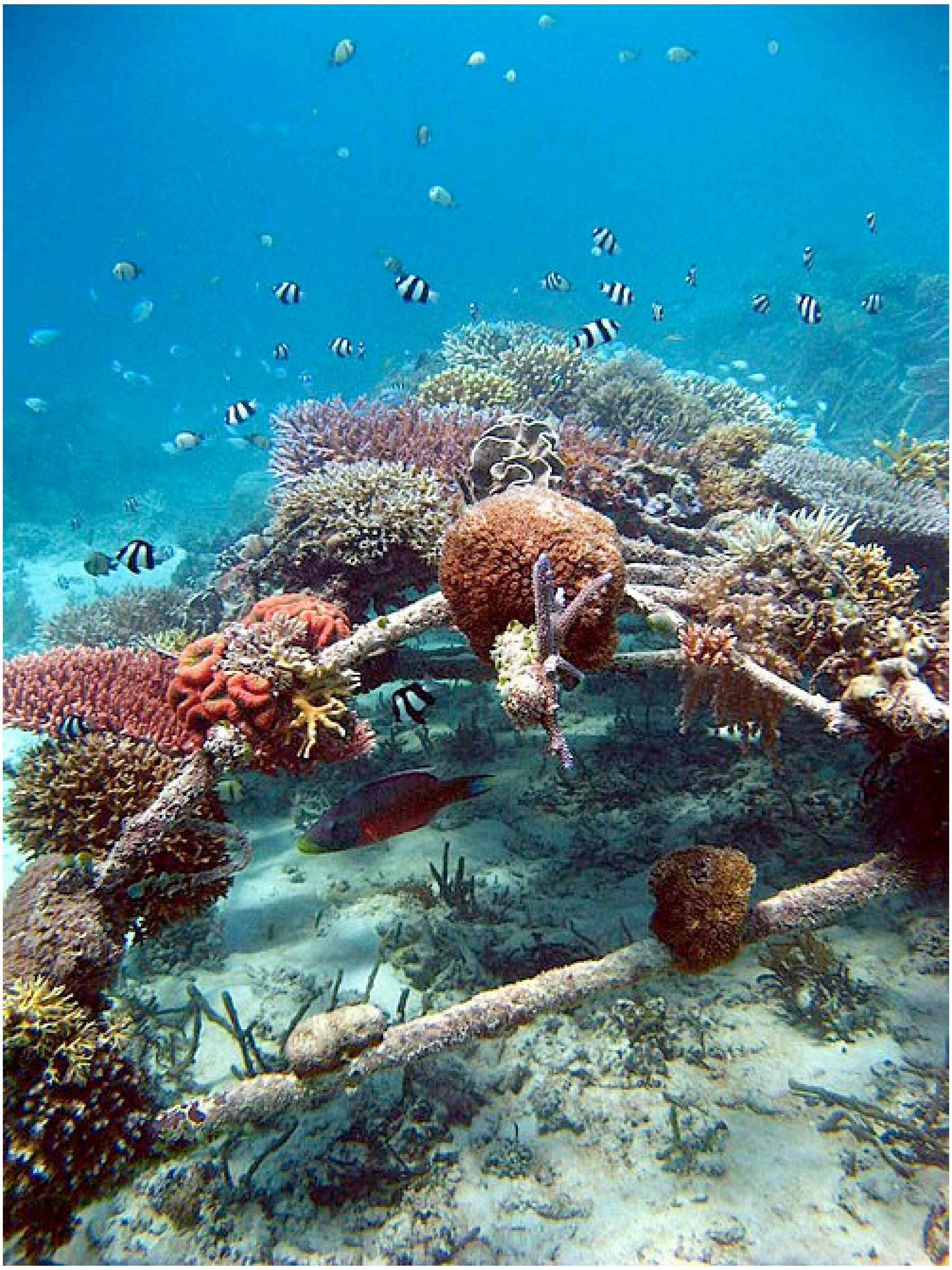

Figure 3: Example of a Biorock reef structure colonized by coral in Indonesia. Image by U.S. Fish and Wildlife Service Headquarters, licensed under CC BY 2.0 **[8]**

Artificial habitats can also be designed as modular “fish cities”. These structures include holes of different sizes so that multiple fish species can use them for shelter. Vertical elements are often incorporated to mimic natural reef cliffs, and the modules can be interconnected to create more complex ecosystems that support a greater diversity of marine life **[9]**.

Figure 4 shows rrreefs’ modular clay reef structure. This example is relevant to Maris Habitats because it shows how repeated modular units can be arranged to create complex underwater habitats.

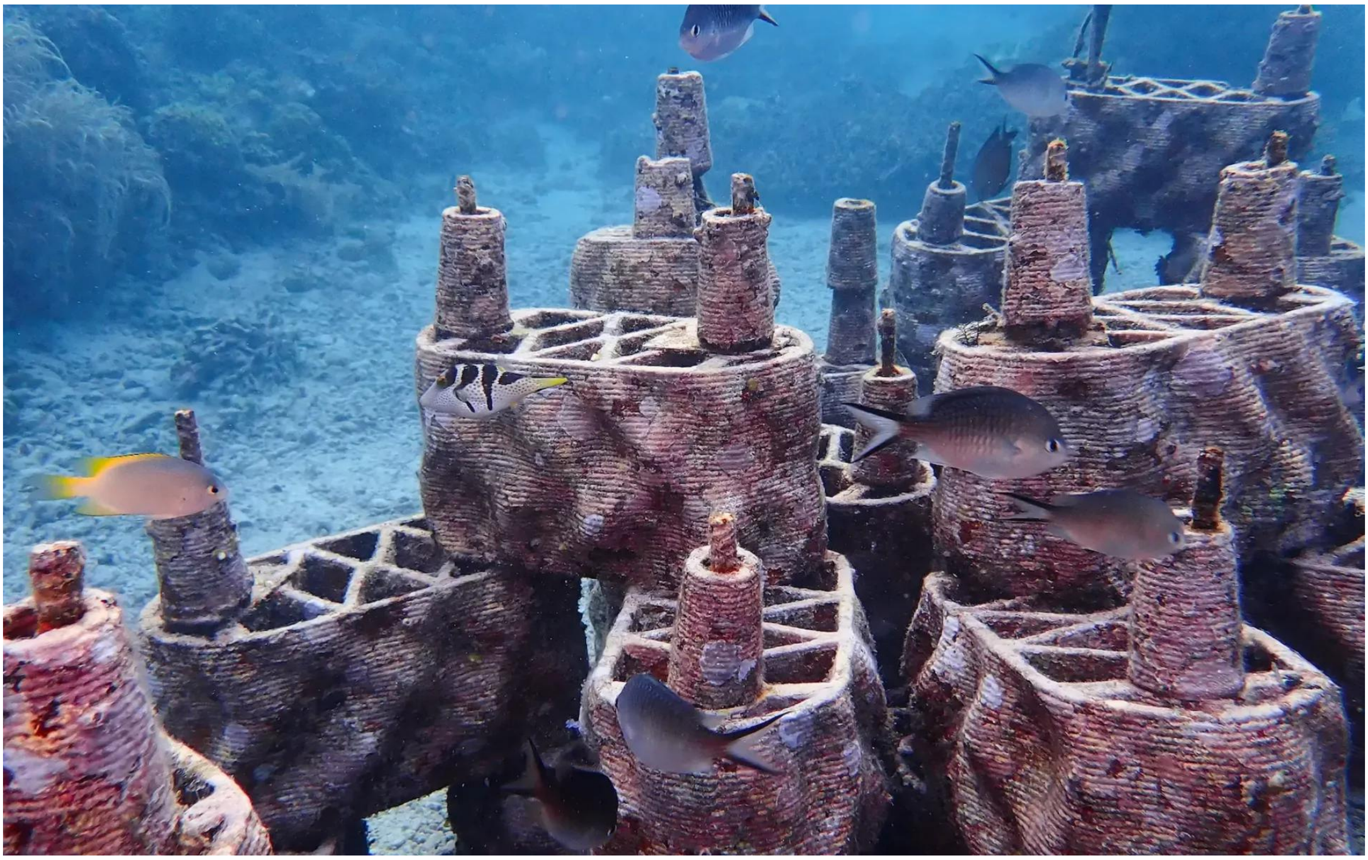

Figure 4: rrreefs modular clay reef structure used for coral reef regeneration **[10]**

Another concept is the development of living seawalls. These are harbor walls or seawalls designed with textured panels and cavities so that marine organisms can attach to them and live on them. Instead of smooth concrete surfaces that support little life, these modified structures create habitats for algae, small invertebrates, and fish **[11]**.

Figure 5shows different living seawall panel designs. The image is useful because it shows how surface texture, cavities, rock pools, and swim-through spaces can be added to hard coastal structures to support marine life.

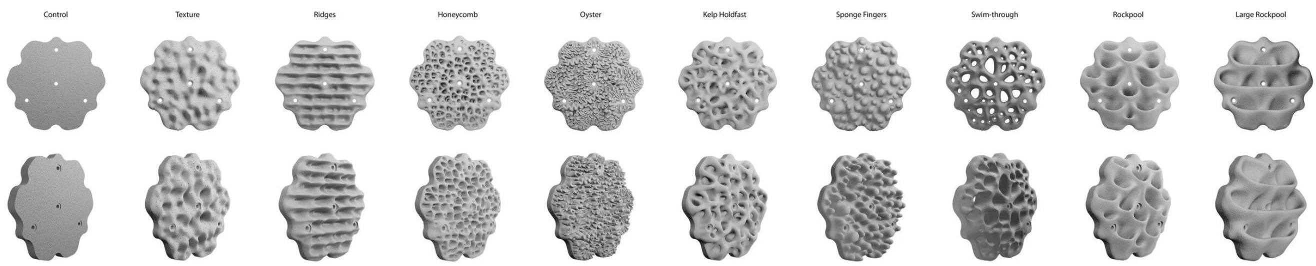

Figure 5: Examples of living seawall panel designs with different textures, cavities, rockpools, and swim-through spaces **[12]**

Several endangered fish species can benefit from these types of artificial habitats, including the Humphead wrasse, Nassau grouper, Atlantic Goliath Grouper, Smalltooth Sawfish, and the European eel. Although many of these species grow quite large, the habitats are especially important for juvenile fish. Young fish can use the structures as shelter and breeding areas, increasing their chances of survival. When more juvenile fish survive, adult populations can recover and thrive. Larger predators may also benefit by hunting around these habitats.

In habitat design, the shape of the structure is often more important than the material used. It is important to include many holes and cavities in different sizes so that different fish species can find suitable shelter. Vertical structures are also important because they mimic natural reef cliffs. In addition, rough surface textures help corals and algae attach and grow on the structures. Finally, ensuring good water flow around the habitat is essential, as it brings nutrients and oxygen that support marine life.

2.3 Companies

This section reviews selected companies related to artificial reef systems and marine habitat infrastructure. The aim is to understand how existing companies approach reef structure, material choice, modularity, and ecological design.

The review also considers whether these solutions include monitoring or environmental data collection as a core feature. This helps identify the position of Maris Habitats as a modular reef infrastructure system with a removable Smart Module and long-term local data logging.

ECOncrete

ECOncrete is a company that develops bio-enhancing concrete technologies for coastal, marine, and offshore infrastructure. Its solutions are designed to improve the ecological performance of concrete structures while still maintaining their engineering function. The company's approach is applied in infrastructure such as ports, seawalls, coastal protection systems, offshore assets, and subsea cable protection.

The main idea of ECOncrete is to make marine infrastructure less biologically poor than conventional smooth concrete structures. This is achieved through changes in concrete composition, surface texture, and structural design. According to the Living Ports project, ECOncrete's rough and irregular surfaces, gaps, and swim-through holes can create habitats, shelter, and breeding spaces for marine organisms **[13]**.

One example of ECOncrete's application is the Living Ports Project at the Port of Vigo. In this project, ECOncrete Coastalocks and ecologically enhanced seawalls were used to create nature-inclusive port infrastructure. As shown in Figure 6, marine growth can develop on these concrete elements over time, showing how infrastructure can maintain its coastal protection function while also supporting ecological value.

However, ECOncrete is different from Maris Habitats in its main focus. Based on the available product descriptions, ECOncrete mainly provides bio-enhancing concrete infrastructure rather than a modular reef system with a removable Smart Module. There is also no clear indication that long-term local data logging is included as a core product feature. Therefore, ECOncrete is a useful benchmark for ecological concrete design, while Maris Habitats aims to add environmental data collection through a removable Smart Module.

Figure 6: ECOncrete bio-enhancing coastal protection units used in the Living Ports Project at the Port of Vigo **[14]**

Reef Design Lab

Reef Design Lab is an Australian design and fabrication company that develops artificial reef and marine habitat solutions. The company describes its work as the design, prototyping, and manufacturing of coastal solutions, with a focus on improving ecological performance in artificial reefs and coastal habitat infrastructure **[15]**.

One of its well-known systems is MARS, which stands for Modular Artificial Reef Structure. MARS is a ceramic 3D-printed modular system designed to construct reef habitat without the need for heavy-duty equipment. The system can be deployed from small boats and assembled by divers, making it suitable for reef restoration projects in locations where large marine construction equipment may be difficult to use **[16]**.

Figure 7 shows Reef Design Lab's MARS system. The image helps illustrate how a modular reef structure can create habitat complexity while still being based on repeated units.

Reef Design Lab is relevant to Maris Habitats because both projects use modular reef structures and focus on creating physical habitat infrastructure in underwater environments. The use of repeated modular units also makes Reef Design Lab a useful benchmark for comparing scalability, deployment, and structural complexity.

However, Reef Design Lab differs from Maris Habitats in its main focus. Based on the available product descriptions, Reef Design Lab mainly focuses on reef design, 3D-printed structures, and project-based marine habitat solutions. There is no clear indication that a removable Smart Module or long-term local environmental data logging is included as a core product feature. Therefore, Reef Design Lab is useful as a benchmark for modular reef design, while Maris Habitats aims to combine

Reef Blocks with a removable Smart Module for long-term environmental observation.

Figure 7: Reef Design Lab's MARS system, a ceramic 3D-printed modular artificial reef structure **[17]**

IntelliReefs

IntelliReefs is a reef restoration initiative and technology platform connected to Reef Life Foundation. It focuses on engineered artificial reef structures made from Oceanite, a bio-enhancing marine substrate designed to mimic natural ocean mineral compounds. According to IntelliReefs, Oceanite can be customized according to site, species, and function, and is used to create reef modules that support coral, seaweed, kelp, and other marine organisms **[18]**.

The main idea of IntelliReefs is to combine material science with reef design. Its Oceanite material is described as a complex mineral matrix held together by a proprietary nanobinder, developed to support diverse species growth and integration into local ecosystems **[19]**. The structures are designed with textured and porous surfaces, as well as small spaces where marine organisms can attach, be protected, and grow over time.

As shown in Figure 8, IntelliReefs uses modular reef units that can be arranged to create complex underwater habitats. These structures are relevant to Maris Habitats because both concepts use modular reef elements and aim to create underwater infrastructure that can interact with the surrounding marine environment.

However, IntelliReefs differs from Maris Habitats in its main focus. Based on the available information, IntelliReefs mainly focuses on Oceanite-based artificial reef structures and marine restoration solutions. There is no clear indication that a removable Smart Module or long-term local environmental data logging is included as a core product feature. Therefore, IntelliReefs is a useful benchmark for alternative reef materials and ecological reef design, while Maris Habitats aims to combine Reef Blocks with a removable Smart Module for long-term environmental observation.

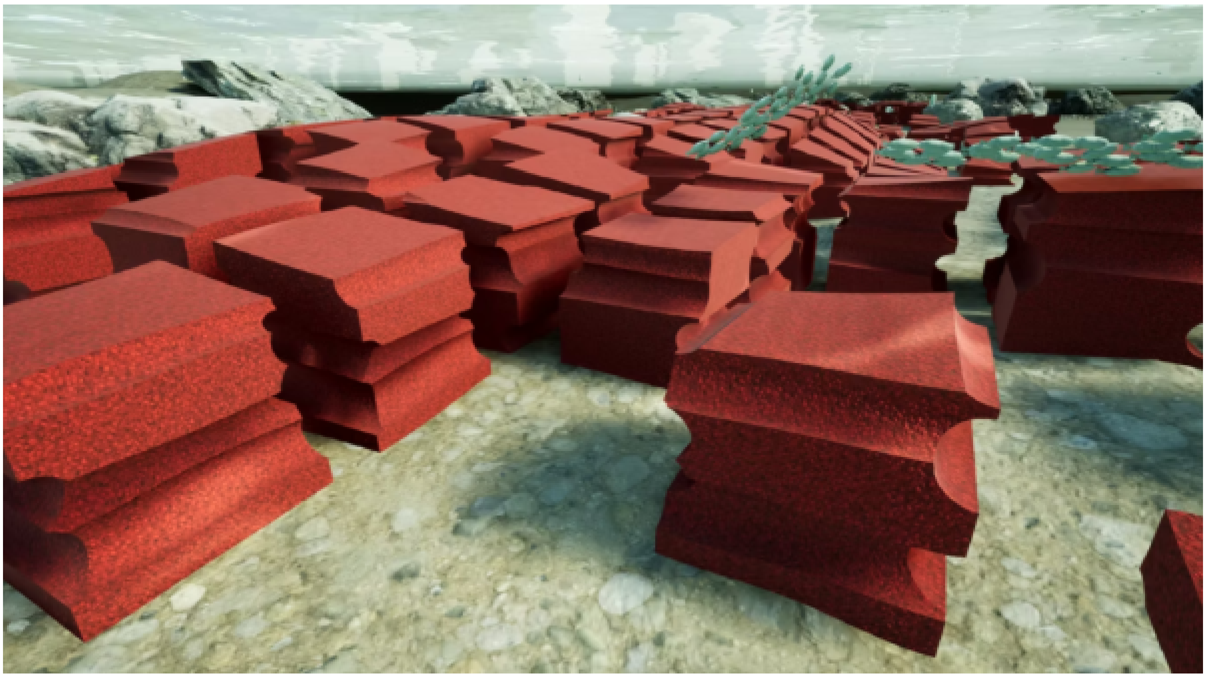

Figure 8: IntelliReefs modular artificial reef structures made with Oceanite material **[20]**

rrreefs

rrreefs is a Swiss start-up that focuses on rebuilding and regenerating degraded coral reefs. The company develops a 3D-printed modular reef system made from clay, designed to support coral growth and provide habitat for marine life **[21]**.

The rrreefs system is based on interlocking clay modules that can be arranged in different shapes depending on the local reef conditions and restoration needs. These modules are designed to mimic natural reef structures, create habitat diversity, and provide sheltered spaces for coral larvae, juvenile fish, crustaceans, and other marine organisms. As shown in Figure 9, the modular units can form complex underwater structures.

rrreefs is relevant to Maris Habitats because both concepts use modular reef structures and aim to create underwater infrastructure that can interact with the surrounding marine environment. The company is also relevant as a business benchmark because it operates as an impact-driven reef restoration start-up and works with local partners to implement reef projects in different countries.

However, rrreefs differs from Maris Habitats in its main focus. rrreefs mainly focuses on coral reef regeneration through 3D-printed clay reef modules and local restoration partnerships. Based on the available product descriptions, there is no clear indication that a removable Smart Module or long-term local environmental data logging is included as a core product feature. Therefore, rrreefs is a useful benchmark for modular reef design and reef restoration business models, while Maris Habitats aims to combine Reef Blocks with a removable Smart Module for long-term environmental observation.

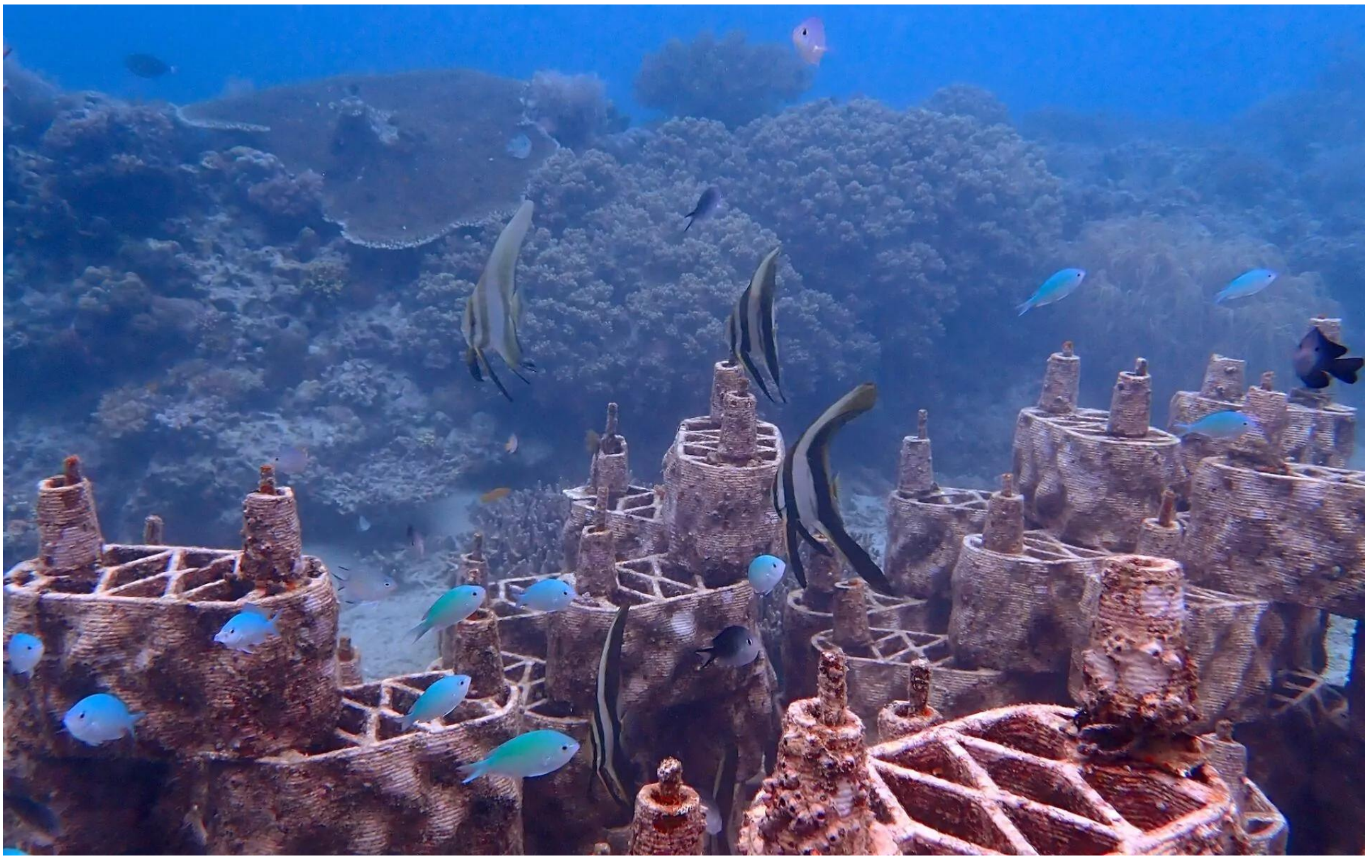

Figure 9: Underwater view of rrreefs modular clay reef structures used for coral reef regeneration [22]

2.4 Comparative Analysis

The selected companies and solutions are evaluated based on criteria such as reef structure, modularity, material approach, monitoring capability, data collection method, maintenance, and suitability for long-term environmental observation.

Since Maris Habitats is designed to observe how an artificial reef and the surrounding marine conditions change over time, the comparison looks beyond ecological enhancement. It also considers whether each solution can collect, store, and retrieve environmental data for later analysis.

Table 1: Comparative overview of selected artificial reef and marine infrastructure companies and the proposed Maris Habitats system

Criteria	**ECOncrete**	**Reef Design Lab**	**IntelliReefs**	**rrreefs**	**Maris Habitats**
Main business focus	Bio-enhancing concrete for marine and coastal infrastructure	Designed and 3D-printed reef structures	Oceanite-based artificial reef restoration	3D-printed modular clay reef restoration	Modular reef infrastructure and environmental data
Product type	Eco-engineered concrete infrastructure units	Modular reef modules and design services	Artificial reef modules made with Oceanite marine substrate	Interlocking 3D-printed clay reef modules	Reef Blocks with an optional removable Smart Module

Criteria	ECOncrete	Reef Design Lab	IntelliReefs	rrreefs	Maris Habitats
Main application	Ports, seawalls, shoreline protection, offshore assets, and subsea cable protection	Reef restoration and marine habitat construction	Coral reef restoration and marine habitat support	Coral reef regeneration and habitat creation	Reef installation, environmental monitoring, and long-term site observation
Modularity	Moderate	High	High	High	High
Ecological design focus	High	High	High	High	Moderate to high
Material / design approach	Bio-enhancing concrete composition, surface texture, and macro-design	Ceramic 3D-printed modular reef structures	Oceanite bio-enhancing marine substrate	3D-printed clay modules inspired by natural reef structures	Basalt fiber-reinforced Reef Blocks and a removable Smart Module
Integrated sensors	No clear indication as a core product feature	No clear indication	No clear indication	No clear indication	Yes, inside the Smartlogger
Real-time data transmission	No clear indication	Not specified	Not specified	Not specified	No
Long-term local data logging	No clear indication as a core product feature	Not specified	Not specified	Not specified	Yes
Data retrieval method	Not specified	Not specified	Not specified	Not specified	SD card / scheduled annual Smartlogger retrieval
Service model	Project-based marine infrastructure solution	Design and project-based reef solution	Restoration project-based solution	Impact-driven reef restoration projects with local partners	Reef Blocks with optional Smart Modules and data service
Main differentiation	Ecological concrete material and infrastructure integration	Complex modular reef design	Alternative Oceanite-based reef material	3D-printed clay reef modules and local restoration partnerships	Removable Smart Module and long-term environmental data

The comparison presented in Table 1 is based on publicly available information from company websites, project descriptions, and related documentation. The selected companies represent different approaches to artificial reef and marine infrastructure development. ECOncrete focuses on bio-enhancing concrete for marine and coastal infrastructure **[23]**. Reef Design Lab focuses on designed and 3D-printed reef structures for artificial reefs and coastal habitat infrastructure **[24]**. IntelliReefs uses Oceanite-based artificial reef structures for reef restoration and marine habitat support **[25]**. rrreefs develops interlocking 3D-printed clay modules for coral reef regeneration **[26]**.

Compared with these companies, Maris Habitats is positioned as a modular reef infrastructure and environmental data solution. The project does not focus only on ecological design or reef structure, but also on collecting environmental data around the reef over time.

The main difference is the removable Smart Module, which includes the Smartlogger and the Smartlogger attachment. The Smartlogger stores data locally and allows scheduled retrieval during maintenance.

2.5 Materials

For this project involving a marine habitat at a maximum depth of 50 m off the Portuguese coast, the materials must withstand a hydrostatic pressure of approximately 5 bar while supporting biological growth and protecting the Smartlogger and its internal monitoring components. To ensure a high level of efficiency and environmental compatibility, various materials used in international restoration efforts have been analyzed.

The selection of materials and the structural design of artificial habitats are fundamental to ensuring both environmental compatibility and long-term viability. For this project, concrete has been identified as the primary material due to its durability and proven use in underwater construction. Its capacity to provide structural integrity against significant environmental stressors, such as salinity, strong currents, and wave action, makes it a common material for creating resilient marine foundations. While the chemical properties of concrete, particularly its initial pH levels, have historically been a point of debate, recent research has shifted the focus toward a more nuanced understanding of its behavior in open marine environments **[27]**.

Studies indicate that the high alkalinity of newly submerged concrete, typically between 12–14, is rapidly diluted by seawater, resulting in no significant long-term detriment to coral growth or benthic colonization **[28]**. This suggests that ecological success depends less on extended curing periods or pH-neutral mixtures and more on the physical attributes of the habitat. Consequently, the following sections will detail how this project prioritizes structural complexity, substrate durability, and hydrodynamic stability **[29]**. By optimizing the weight-to-complexity ratio and ensuring low water absorption, the design can help ensure that these structures remain stationary during extreme weather events while providing the necessary niches for biodiversity to thrive **[30]**.

Based on the research and articles reviewed, the following subsection evaluates different material options, ranging from traditional foundations to innovative biocompatible substrates, in order to select the most suitable materials for this specific implementation.

2.5.1. Structural Materials

A. Bacterial (Self-healing) High-Strength Concrete (HSC)

This material incorporates bacterial spores, specifically *Bacillus sphaericus* (strain ATCC 14577), which remain dormant until a crack occurs. Water ingress activates the bacteria, which then precipitate calcium carbonate to seal the crack **[31]**.

- Pros: Achieves **96 % recovery in water tightness** within 56 days of seawater immersion **[32]**. It maintains structural integrity above **100 MPa**, which is well above the hydrostatic pressure expected at 50 m. It significantly reduces rebar corrosion by sealing entry points for chloride ions **[33]**.
- Cons: Higher complexity in mixing and requires specific nutrients like calcium lactate and urea **[34]**.
- Price: Estimated at **180 €/m^3 – 260 €/m^3**.

B. Basalt Fiber-Reinforced Polymer (BFRP)

Basalt fibers, derived from natural volcanic rock, are used to reinforce concrete or as standalone composite laminates [35].

- Pros: **Naturally non-corrosive** and chemically stable in aggressive saline environments [36]. Vacuum infusion manufacturing can produce laminates with flexural strength up to **400 MPa** [37]. It provides a more resilient, damage-tolerant failure mode compared to the brittle collapse of traditional reinforced concrete [38].
- Cons: Slightly lower peak flexural strength compared to glass fibers, although superior in long-term durability and environmental footprint [39].
- Price: Estimated at **160 €/m^3 – 220 €/m^3**.

C. Geopolymer Gel Concrete

A cement-free binder using materials like fly ash and metakaolin modified with nano-silica (SiO_2) [40].

- Pros: Significantly **lower CO_2 footprint** than Portland cement [41]. It shows superior resistance to chloride and sulfate attack in "wet-thermal" marine environments [42].
- Cons: Higher production costs currently limit wide adoption [43].
- Price: Estimated at **150 €/m^3 – 200 €/m^3**.

D. ECOncrete® / Sulfoaluminate Cement (SAC)

A proprietary concrete mix designed to reduce surface alkalinity to a neutral pH [44].

- Pros: Surface **pH of 9–10** (closer to seawater pH of around 8) promotes the settlement of "ecosystem engineers" like oysters, serpulid worms, and coralline algae. These organisms provide **bioprotection**, adding a calcified layer that strengthens the structure and limits oxygen/chloride penetration [45].
- Cons: Requires specialized design to ensure the lower pH does not compromise the protection of internal steel if used.
- Price: Estimated at **140 €/m^3 – 180 €/m^3**.

E. Recycled Glass (Partial Aggregate Replacement)

Crushed waste glass used to replace up to 30 % of fine aggregates in the concrete mix [46].

- Pros: Improves **chemical resistance** and reduces water absorption [47]. It offers an eco-friendly way to utilize waste while maintaining sufficient compressive strength for marine applications [48].
- Cons: Replacing more than 30 % of aggregate leads to a **significant reduction in compressive strength** [49].
- Price: Estimated at **90 €/m^3 – 140 €/m^3**.

F. Biorock (Mineral Accretion)

Uses low-voltage DC electricity to precipitate minerals (limestone) directly from seawater onto an iron frame.

- Pros: Accelerates biological growth by **400 %** and allows the structure to **self-repair** after impacts [50].
- Cons: Requires **constant power** from a buoy; if the power is interrupted, the iron frame

corrodes rapidly.
- Price: Base infrastructure **120 €/m³ – 160 €/m³** (excluding electrical components).

2.5.1.1 Comparative Table

The materials evaluated in the previous subsection are summarized in Table 2.

Table 2: Comparative table for materials evaluated

Material	**Primary Requirement Met**	**Pros**	**Cons**	**Estimated Price / m³**
Bacterial HSC	Longevity / pressure resistance	Autonomous repair; 96 % watertight	High complexity	180–260 €
Basalt Reinforcement	Corrosion resistance	Non-corrosive; volcanic origin	Lower flexural peak	160–220 €
Geopolymer Gel Concrete	Low carbon and chemical resistance	Lower CO_2; chloride and sulfate resistance	Higher production cost	150–200 €
ECOncrete®	Marine-life friendly	Neutral pH; bioprotection	Specific mix needs	140–180 €
Recycled Glass	Sustainability	Increased chemical resistance	Strength loss above 30 %	90–140 €
Biorock	Life promotion	4:1 growth; self-repairing	Power dependent	120–160 €

2.5.1.2 Materials for Prototype vs. Final

The final Maris Habitats product and the prototype have different material requirements because they have different purposes. The final product is intended for long-term underwater deployment, while the prototype is mainly used to validate the Reef Block shape, assembly process, Smartlogger attachment, and basic structural concept under controlled conditions.

For the final product, basalt fiber-reinforced concrete was selected as the intended material for the Reef Blocks. This material was chosen because the final Reef Blocks must remain stable on the seabed and resist long-term marine exposure, including saltwater, currents, wave action, and material degradation. Basalt fiber-based materials are suitable for marine applications because they offer mechanical performance and resistance to chemical and environmental degradation **[51]**. Concrete structures in marine environments must also be designed carefully because seawater exposure, chloride and sulfate attack, corrosion processes, and wave action can cause deterioration over time **[52]**.

For the prototype, the material selection was based on practicality, cost, availability, and ease of production. The prototype does not need to prove full marine durability because it is not intended for real underwater deployment. Instead, it should help the team check whether the Reef Block shape, Smartlogger position, Smartlogger attachment, assembly logic, and general handling are suitable.

During the prototype planning stage, three material options were considered:

Option 1: Polymer clay model

Polymer clay was considered during the early design stage because it can be shaped by hand and hardened in an oven. This makes it useful for quick form exploration when the team needs to test different shapes before deciding on the final Reef Block geometry. Polymer clay remains soft until it is baked, and baking is used to cure the material so that the shape becomes hard **[53]**. It can also be stretched, cut, rolled, molded, stacked, and sculpted before baking, which makes it practical for small visual models and early design tests **[54]**.

However, polymer clay was not selected as the main prototype material because it is very different from the final concrete-based product. It cannot represent the real weight, concrete surface texture, porosity, or handling of the final Reef Block. It is also limited by oven size and is not suitable for validating structural performance, Smartlogger attachment, seabed stability, or long-term marine durability.

- **Pros:** Easy to shape, easy to modify before baking, low cost, and useful for early form exploration.
- **Cons:** Very different from the final concrete-based material, limited by oven size, does not represent real Reef Block weight, texture, porosity, or handling, and is not suitable for technical validation.

Option 2: Cement-based prototype cast with a 3D-printed mold

A cement-based prototype is closer to the final concrete-based product because it can better represent the general appearance, surface texture, weight, and handling of the Reef Block. Concrete is widely used for artificial reef construction and can be used to create complex shapes for marine habitat structures **[55]**. In this approach, PLA filament is used to produce a 3D-printed mold, and cement is poured into the mold and left to cure. Therefore, PLA is not used as the final material of the Reef Block prototype, but as a tooling material for shaping the cement-based model. PLA is suitable for this purpose because it is commonly used for rapid prototyping and can also be used for mold inserts or casting-related applications **[56]**, **[57]**.

This option allows the team to combine the geometric accuracy of 3D printing with the more realistic material behavior of a cement-based prototype. It is also low-cost and possible to produce locally. However, the prototype is not intended for real underwater deployment, and normal cement does not fully represent the final basalt fiber-reinforced concrete. Therefore, this option can be used to check the general shape, handling, assembly, and Smartlogger attachment, but it cannot prove long-term durability or full structural performance in marine conditions. For the final product, basalt fiber-reinforced concrete would still be required because it is more suitable for long-term marine exposure and resistance to chemical and environmental degradation **[58]**, **[59]**.

- **Pros:** Similar appearance to the final material, more realistic weight and texture, accurate geometry from the 3D-printed mold, low cost, and suitable for checking general shape, handling, assembly, and Smartlogger attachment.
- **Cons:** Does not fully represent basalt fiber-reinforced concrete, harder to modify after casting, requires curing time, and is not suitable for proving long-term marine durability because the prototype is only intended for controlled testing.

Option 3: Fully 3D-printed scale model or 3D-printed details

A fully 3D-printed model can represent the geometry of the Reef Block, Smartlogger, and Smartlogger attachment accurately. 3D printing is useful for rapid prototyping because it allows detailed shapes to be produced and modified more easily during the design process **[60]**. For this reason, this option can be useful for checking the modular shape, assembly process, Smartlogger attachment, and packaging concept before producing a cement-based prototype.

However, this option means that the Reef Block itself is made from 3D-printed plastic rather than cement or concrete. Because of this, the material properties are different from the final concrete-based product. A fully 3D-printed plastic model cannot represent the real weight, concrete surface texture, porosity, or marine durability of the final Reef Block. Therefore, it is useful for geometry and assembly validation, but not for checking realistic handling, seabed stability, or material behavior.

In the selected prototype approach, 3D printing is used mainly to produce the PLA mold for cement casting, rather than to make the final Reef Block prototype itself. Additional 3D-printed parts may still be used for small details or Smartlogger attachment features that require accurate geometry.

- **Pros:** Accurate geometry, easy to modify, fast to produce, suitable for assembly checks, Smartlogger attachment tests, packaging checks, and presentation.
- **Cons:** Different from the final material, does not represent real Reef Block weight, concrete surface texture, porosity, or marine durability, and is not suitable for material durability or seabed stability testing.

2.5.2 Sensor Placements

Designing a successful marine habitat involves a delicate technical paradox. On one hand, the project's primary objective is to encourage biological colonization and the growth of marine life; on the other, the integrated sensors require direct, unobstructed contact with seawater to maintain accuracy. This necessity creates a significant challenge, as the very “bio-friendly” environment the team aims to foster can lead to marine biofouling on sensitive equipment, which critically compromises data reliability and sensor sensitivity **[61]**.

To resolve this conflict, the strategy focuses on three integrated design pillars. First, a careful selection of housing materials must be made to support structural durability while protecting the internal components. Second, specialized antifouling coatings should be evaluated to prevent accumulation on sensor windows without leaching harmful chemicals into the surrounding habitat. Finally, the spatial distribution of the sensors must be strategically planned to allow for clear measurements while minimizing their exposure to rapid biological growth. This balanced approach ensures that the ecological goals do not come at the expense of long-term monitoring precision.

When positioning sensors, it is important to consider factors that may influence measurement accuracy, such as turbulence and disturbed flow conditions. Careful placement can significantly improve the reliability and consistency of the collected data.

The Smartlogger, which contains the sensors, is mounted at the top of the Smartlogger attachment to reduce the risk of interaction with seabed sediment. However, the sensors themselves should not be placed at the very top surface, as this location is more prone to biofouling, sediment accumulation, and coverage by marine organisms, which can degrade sensor performance over time.

Instead, the sensors are preferably mounted on a side surface where there is sufficient and consistent water flow. Positioning them slightly above the seabed further reduces the risk of sand and sediment deposition, ensuring more stable and accurate measurements. This placement also allows the surrounding water to circulate more freely around the sensors, which is particularly important for measurements such as conductivity, where undisturbed water flow is essential for obtaining reliable data.

In addition, the Smartlogger is positioned to be as accessible as possible to facilitate maintenance operations, such as sensor cleaning, battery replacement, and data retrieval.

2.5.2.1 Materials for Housing

The Smartlogger housing material must protect the internal electronics from high pressure and corrosion while maintaining long-term durability in seawater environments.

Titanium alloy (TC4) or **316 L stainless steel** are recommended for pressure resistance and durability **[62]**. For deeper or long-term deployments, titanium can be considered because it is described as a corrosion-resistant housing material suitable for long-term deployment in harsh environments, with a depth rating up to 6000 m **[63]**.

2.5.2.2 Antifouling Coatings

Even with durable housing materials, marine organisms may attach to exposed surfaces over time. For this reason, antifouling coatings are considered to reduce biological growth on sensors and maintain measurement accuracy.

- **Polydimethylsiloxane (PDMS):** A non-toxic, “fouling-release” coating that reduces the adhesion of algae and barnacles **[64]**.
- **Camptothecin (CPT)-based Paint:** A natural compound that has shown virtually no macrofouling after nine months of immersion **[65]**.
- **Slippery Liquid-Infused Porous Surfaces (SLIPS):** These provide exceptional resistance to organism attachment even in stagnant water **[66]**.

2.5.3 Biologic and Geographical analysis

Fish structure

Fish populations are generally associated with habitats that exhibit high structural complexity and spatial heterogeneity **[67]**. Research suggests that complex environments provide essential ecological resources necessary for survival, including food availability, shelter from predators, and suitable areas for reproduction. Structural features such as crevices, cavities, and irregular surfaces may create microhabitats that support a greater diversity of marine organisms and increase the overall ecological value of reef systems.

Artificial and natural reefs typically contain irregularities and indentations that form small shelters or “nooks”, which can serve as refuge areas for fish and other marine organisms. These structural features are believed to reduce predation risk and provide protected spaces where fish can rest or reproduce.

Studies also indicate that fish communities tend to perform better in connected habitat mosaics rather than isolated structures **[68]**. Networks of habitats may facilitate movement, feeding opportunities, and ecological interactions between species, which can contribute to more stable and diverse marine ecosystems.

Location

The location of artificial reefs plays a key role in determining their effectiveness. The chosen site should encourage marine life to settle while avoiding interference with human activities such as shipping routes or commercial fishing areas. Water depth is another important consideration. Reefs

placed too deep may not receive enough sunlight to support the growth of marine plants like algae, whereas reefs that are too shallow can be more vulnerable to damage from storms or human activity **[69]**.
Most of the artificial reef projects are placed at depths of 10-20 meters, but it all depends on which species and what type of marine life the reefs intended for.

2.6 Summary

Chapter 2 gives an overview of existing artificial reef concepts, relevant companies, material choices, sensor challenges, and biological and geographical factors. It shows that Maris Habitats differs from many existing solutions by combining modular Reef Blocks with a removable Smart Module for long-term local data logging. The chapter also highlights that successful reef design depends on durable marine materials, structural complexity, suitable sensor placement, and careful site selection.

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