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5. Eco-efficiency Measures for Sustainability

This chapter presents the sustainability aspects of Maris Habitats by looking at environmental, economic, and social impacts. It also explains how the product's life cycle is considered from material selection and production to maintenance and end-of-life.

5.1 Introduction

This chapter examines the environmental, economic and social dimensions of the project, as well as the product's life cycle, in order to assess its overall sustainability. The aim is to highlight the considerations taken to minimize negative environmental impacts when introducing artificial structures into marine ecosystems.

Particular attention is given to ensuring that the solution does not further disrupt or degrade existing ocean environments. This includes evaluating how the design, material selection, and long-term use of the product can prevent pollution and reduce ecological harm. By adopting a lifecycle perspective, the chapter also addresses how the product can be managed responsibly from production to end-of-life.

5.2 Environmental

This section considers the environmental impact of the project using principles inspired by the butterfly diagram, a model that represents circular material flows **[1]**. The model distinguishes between biological processes, where materials safely integrate into natural systems, and technical processes, where products are maintained, reused, and recycled to extend their lifespan (see Figure 1).

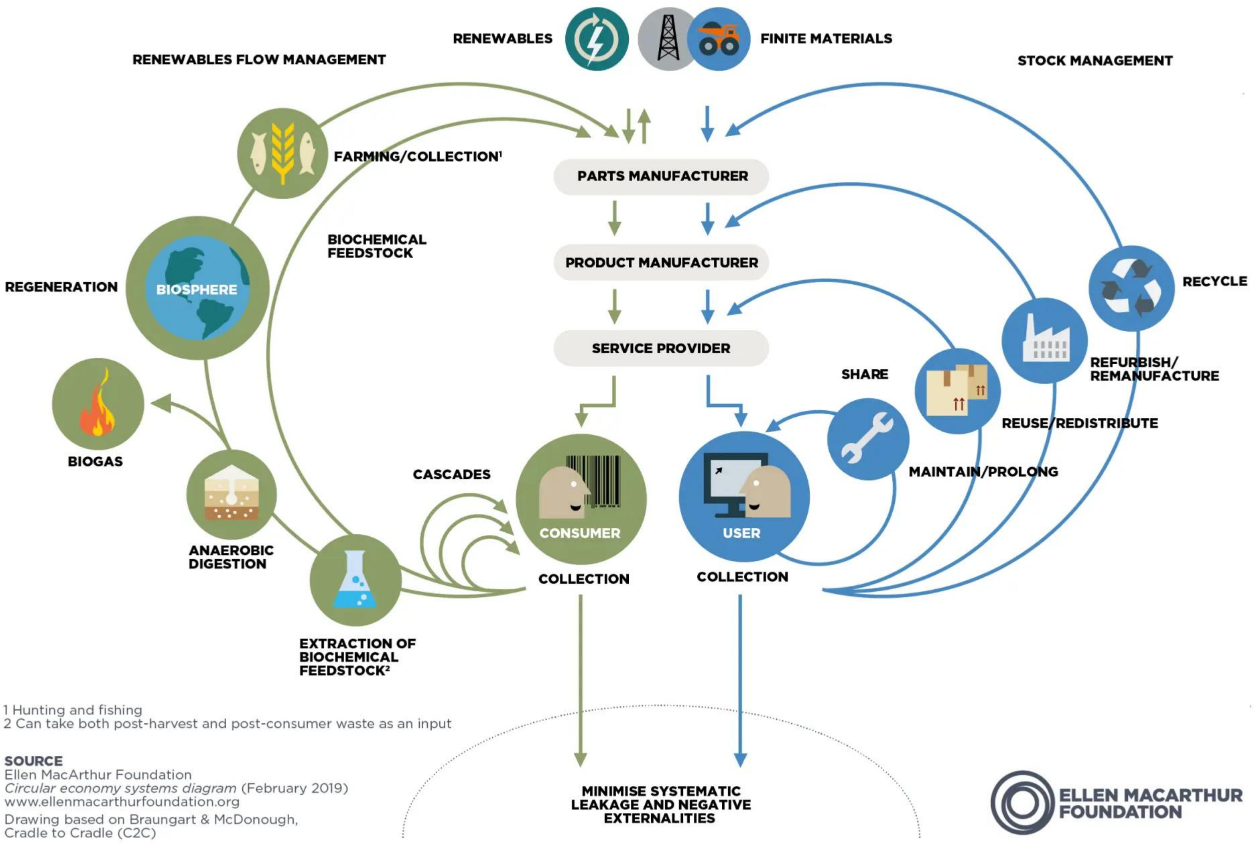

Figure 1: Butterfly diagram **[2]**

The Maris Habitats concept reflects these principles by combining long-term environmental integration with efficient use of technical components. From a biological perspective, the habitat is designed to support marine colonization over time. The use of non-toxic and durable materials allows algae, microorganisms, and small marine species to attach and grow on the structure, contributing to biodiversity enhancement **[3]**.

From a technical perspective, the system is designed with longevity and adaptability in mind. The modular concrete habitat structure is intended to remain underwater for long periods, while the electronic components are housed in a easily detachable waterproof enclosure attached to the habitat. This enclosure contains the battery, microcontroller, and data storage system. Sensor probes are mounted through the enclosure and remain exposed to seawater to measure environmental conditions such as pH, conductivity, pressure, and temperature. This modular design allows maintenance or replacement of electronic components without removing the entire habitat structure.

Maintenance requirements are reduced through the use of durable materials that can withstand harsh marine conditions. When maintenance is required, divers can retrieve stored data and replace batteries without disturbing the reef structure. This reduces unnecessary material replacement and extends the operational life of the system.

The project also considers the reuse of technical components. If monitoring is no longer required, electronic components such as sensors, batteries, and storage devices can be removed and reused in future installations.

For the prototype, conventional concrete or 3D printing may be used to reduce costs, while the final design uses basalt fiber-reinforced concrete to improve durability and corrosion resistance in marine environments. This approach reduces environmental impact while maintaining long-term functionality.

5.3 Economical

The economic aspect of Maris Habitats is mainly related to the long-term benefits created through ecosystem restoration and its integration with existing marine infrastructure. By improving marine biodiversity and supporting fish population growth, the system may help increase fishery productivity over time. This can create economic benefits for coastal communities that depend on fishing as a source of income and food.

Previous studies have shown that artificial reefs can increase fish biomass and support the development of fisheries, which can lead to economic improvements in coastal areas **[4]**. In this project, this idea is applied through habitat structures that provide shelter and breeding areas for marine species.

The system is also designed to be integrated with existing marine infrastructure, such as offshore wind farms or coastal protection systems. This approach reduces the need for completely new structures and allows existing installations to gain additional ecological functions, improving resource efficiency.

The integration of sensors adds another layer of economic value. The system collects environmental data that can be used for research, monitoring, and decision-making. In this project, this data supports more efficient marine resource management and may help reduce costs related to ineffective environmental monitoring.

Another important aspect is the modular and scalable design of the system. Habitat units can be deployed gradually and adapted to different marine environments, reducing the need for large initial investments. This allows pilot projects to be tested before full-scale deployment.

The modular monitoring system also helps reduce maintenance costs. Instead of replacing the entire structure in case of failure, only specific electronic components need to be repaired or replaced. This improves operational efficiency and reduces long-term costs.

In addition, the project can benefit from collaboration with public institutions, research organizations, and environmental programs. Marine restoration and biodiversity protection are increasingly supported by sustainability policies and funding initiatives **[5]**. This creates opportunities for financial support through grants and public-private partnerships.

Although the initial investment may be relatively high, the project can create long-term value through ecosystem restoration, fishery support, and improved coastal protection **[6]**. For this reason, Maris Habitats can be considered both environmentally sustainable and economically viable in the long term.

5.4 Social

The integration of environmental sensors also creates social value by generating data that can be used by research institutions and environmental organizations for marine monitoring and scientific research. This can improve understanding of marine ecosystems and support better environmental decision-making.

The project is also aligned with the market strategy by focusing on partnerships with offshore wind farms, coastal authorities, research institutions, and environmental organizations **[7]**. By integrating artificial habitats into existing marine infrastructure, the project promotes collaboration between technical and environmental stakeholders while reducing the need for additional construction.

In the long term, this approach can support sustainable fisheries, marine conservation efforts, and stronger cooperation between industries involved in ocean management.

5.5 Life Cycle Analysis

The life cycle of the project is considered from material selection to end-of-life, with the aim of reducing environmental impact while maintaining long-term functionality.

In this project, the material phase focuses on choosing durable and environmentally responsible materials. The final design uses basalt fiber-reinforced concrete. Basalt fibers are made from natural volcanic rock and are known for their resistance to corrosion and chemical stability in seawater, which makes them suitable for marine environments **[8]**.

During the manufacturing phase, the reef structure is produced through concrete casting, while the monitoring system is assembled separately as a detachable smart block. This smart block contains the battery, microcontroller, SD card, and sensors. Keeping the electronic components separate helps avoid embedding electronics directly into the permanent structure and reduces unnecessary material waste.

The testing phase focuses on checking both the structural performance of the habitat and the operation of the monitoring system. Special attention is given to battery life, waterproof protection, sensor accuracy, and reliable data collection because these factors affect maintenance needs.

The structure is also designed for long-term use in marine environments. Its geometry includes cavities and irregular surfaces that help algae, microorganisms, and small marine species attach to the structure over time.

To reduce environmental risks, the smartlogger is designed as a removable unit that is not cast into the main reef structure. It is mounted on a separate support frame and secured to the module block with a chain, which keeps the smart box connected to the reef structure and gives the diver a clear point to attach a hook or line. During maintenance, battery replacement, data collection, or repairs, only the smart box is lifted from the seabed, while the main reef structure stays in place. This also helps reduce the risk of long-term marine pollution from electronic components.

At the end of its life cycle, the structure is intended to remain in the marine environment and continue functioning as an artificial reef that supports biodiversity **[9]**. Electronic components can be removed and reused in future systems, which helps reduce waste.

5.6 Summary

This chapter has examined the environmental, economic, and social dimensions of the project, together with a lifecycle perspective, in order to evaluate its overall sustainability. The analysis highlights the importance of minimizing environmental impact while ensuring long-term functionality, economic viability, and social value.

Based on this sustainability analysis, the team selected a modular habitat design combined with a separate monitoring system and the use of basalt fiber-reinforced concrete as the primary structural material. This choice is supported by its durability, resistance to marine conditions, and suitability for long-term deployment without causing environmental harm. In addition, the separation of electronic components from the main structure contributes to reducing pollution risks and improving resource efficiency.

Consequently, the solution was designed with features that support sustainability throughout its lifecycle. These include a structure that can integrate into the marine ecosystem over time, a modular and retrievable sensor system that enables maintenance without disturbing the habitat, and a design that promotes marine colonization through varied shapes and surface characteristics. Together, these elements ensure that the system not only minimizes negative environmental impacts but also contributes positively to marine biodiversity and long-term ecosystem health.

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[1], **[2]** Ellen MacArthur Foundation, 2021. *The Circular Economy System Diagram (Butterfly Diagram).*
[3] DipNDive, 2023. *The Ethical Debate Around Artificial Reefs: Conservation or Tourism Ploy?.*
[4] Artificial reef preparation
[5] Andrew Deutza, Geoffrey M. Healb, Rose Niuc, Eric Swansonc, Terry Townshendc, Zhu Lic, Alejandro Delmard, Alqayam Meghjid, Suresh A. Sethid, John Tobin-de la Puente, 2020. Financing Nature: Closing the Global Biodiversity Financing Gap. *Paulson Institute*, na, na.
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[9] Blue is the new green – Ecological enhancement of concrete based coastal and marine infrastructure. *Ecological Engineering*, 84, 2015, pp.260-272, ISSN 0925-8574.