

School of Design
Master of Science in Design & Engineering

Huiro: A *more-than-human* design research project for situated kelp forest restoration

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Huiro
Common name in Chile for large brown seaweeds of the genus *Macrocystis.*
More than a resource, huiro is structure, habitat, and submerged territory.

To my dad.

Abstract

Kelp forests are complex multi-species ecosystems whose regeneration requires approaches that integrate ecological, material, and territorial knowledge. In Chile, historical overharvesting of *Macrocystis pyrifera* has resulted in fragmented populations that struggle to re-establish stable benthic structures. Situated within a **case study in Coliumo, Biobío Region (Chile)**, this thesis addresses restoration in a regulated and socio-ecologically complex coastal territory.

The research positions design as a **translational and more-than-human practice** capable of mediating between marine ecological dynamics, scientific inquiry, and coastal conditions. Developed through a **transdisciplinary collaboration** involving designers, engineers, and marine scientists, the project adopts a **research-through-design methodology** in which material experimentation functions simultaneously as intervention and learning process.

Rather than proposing a finalized product, the thesis develops a **modular experimental system** conceived as a temporary structural mediator supporting early-stage kelp establishment under dynamic marine conditions. Material selection integrates concrete durability research, eco-engineering principles, and additive manufacturing constraints to align mechanical performance with ecological compatibility.

Kelp is approached not as a passive beneficiary but as an active biological agent whose growth dynamics inform structural response. The resulting intervention operates as prototype, ecological mediator, and epistemic device, generating situated knowledge while contributing a design framework for adaptive marine restoration practices.

Sommario

Le foreste di kelp sono ecosistemi complessi e multispecifici la cui rigenerazione richiede approcci capaci di integrare conoscenze ecologiche, materiali e territoriali. In Cile, il sovrasfruttamento storico di Macrocystis pyrifera ha prodotto popolazioni frammentate che faticano a ristabilire strutture bentoniche stabili. Inserita in un **caso studio a Coliumo, Regione del Biobío (Cile)**, questa tesi affronta la restaurazione in un territorio costiero regolato e socio-ecologicamente complesso.

La ricerca posiziona il design come **pratica traslazionale e more-than-human**, capace di mediare tra dinamiche ecologiche marine, indagine scientifica e condizioni costiere. Sviluppato attraverso una **collaborazione transdisciplinare** tra designer, ingegneri e scienziati marini, il progetto adotta una **metodologia di research-through-design** in cui la sperimentazione materiale funziona simultaneamente come intervento e come processo di apprendimento.

Piuttosto che proporre un prodotto definitivo, la tesi sviluppa un **sistema sperimentale modulare** concepito come mediatore strutturale temporaneo a supporto dell'insediamento iniziale del kelp in condizioni marine dinamiche. La selezione dei materiali integra ricerche sulla durabilità del calcestruzzo, principi di eco-engineering e vincoli della manifattura additiva, con l'obiettivo di allineare prestazioni meccaniche e compatibilità ecologica.

Il kelp non è considerato un beneficiario passivo, ma un agente biologico attivo le cui dinamiche di crescita informano la risposta strutturale. L'intervento risultante opera come prototipo, mediatore ecologico e dispositivo epistemico, generando conoscenza situata e contribuendo a un framework di design per pratiche adattive di restaurazione marina.

Acknowledgements

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1. Introduction

Figure 1: Underwater marine environment.
Source: Adobe Stock.

1.1 Background and Motivation

Environmental degradation has become one of the defining challenges of our time. Climate change, biodiversity loss, and ecosystem decline are no longer abstract concerns but processes directly affecting natural environments and human societies.Within this global context, oceans play a fundamental role. They regulate climate, absorb excess heat and carbon dioxide, support vast biodiversity, and sustain coastal livelihoods and global economies (Gaines et al., 2023; IPCC, 2022).

The ocean has absorbed more than 90% of the excess heat generated by greenhouse gas emissions, leading to measurable warming, acidification, deoxygenation, and sea-level rise (IPCC, 2022). These changes are not only ecological but socio-economic. Ocean-based industries contribute approximately USD 2.5 trillion annually to the global economy and support hundreds of millions of jobs. Climate-induced declines in ocean health are projected to impose severe economic losses over the coming decades (Gaines et al., 2023). Yet marine ecosystems remain among the least visible to most people, making their degradation difficult to perceive and address (UNEP, 2023). The ocean's scale, opacity, and dynamism complicate both observation and intervention. Ecological interactions unfold across multiple spatial and temporal scales in non-linear ways that resist simplification.

Marine environments are therefore increasingly understood as **complex social-ecological systems (SES)**, composed of interacting subsystems such as resource units, governance structures, users, and ecological processes (Ostrom, 2009).

These systems are characterized by **feedback loops, pervasive uncertainty, and multi-scalar interactions** (Folke et al., 2016). Scientific disciplines, however, often analyze these subsystems separately, limiting cumulative understanding and coordinated action (Ostrom, 2009).

This **fragmentation** is particularly evident in marine contexts. While scientific research generates increasing amounts of data, the translation of knowledge into context-sensitive action remains uneven. Marine governance, community practices, and scientific research frequently operate in parallel rather than in integration. Studies on marine knowledge exchange highlight persistent barriers between researchers, policymakers, and local actors, limiting effective implementation (Cvitanovic et al., 2015).

These dynamics resonate with what Rittel and Webber (1973) describe as ***"wicked problems"***: issues that resist definitive formulation, involve multiple stakeholders, and evolve over time. Environmental degradation in marine contexts embodies these characteristics, unfolding within **ecological uncertainty and institutional complexity**.

Recent international initiatives, such as the United Nations Decade of Ocean Science for Sustainable Development, emphasize the need not only for more scientific data but for stronger connections between science, society, and practice (UNEP, 2023). The IPCC Special Report on the Ocean and Cryosphere stresses the urgency of adaptive, forward-looking strategies that integrate ecological and socio-economic dimensions (IPCC, 2022). These calls signal a shift from isolated technical responses toward more **integrated, situated approaches.**

- Socio-ecological fragmentation in marine restoration contexts

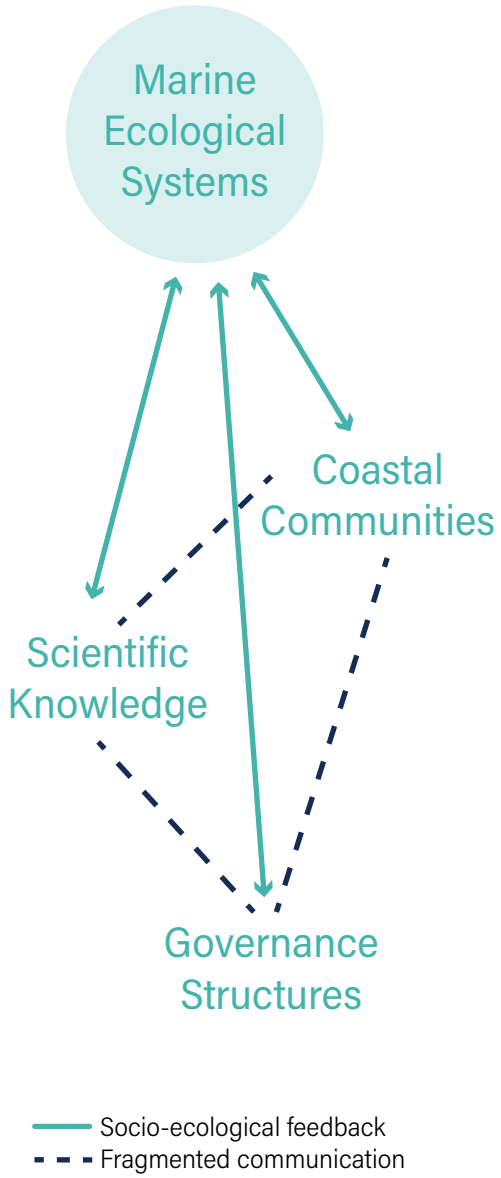


Figure 2. Fragmented socio-ecological coordination (author's own elaboration).

From a design perspective, this context raises critical questions. Design has increasingly been understood not merely as object production, but as a practice capable of **mediating between actors, systems, and material conditions** (Manzini, 2015). **Translational and interdisciplinary design approaches** emphasize the capacity of design to operate between knowledge domains, transforming insights into situated forms of intervention (Irwin, 2015).

In complex environmental contexts, design may contribute not by offering definitive solutions, but by structuring processes of inquiry, experimentation, and relational engagement. Furthermore, contemporary ecological thinking challenges anthropocentric framings of intervention. ***More-than-human*** **perspectives** argue for recognizing humans as participants within entangled multispecies worlds rather than external managers of nature (Haraway, 2016).

The motivation for this thesis emerges from this intersection: the accelerating degradation of marine environments, the systemic complexity of social-ecological systems, the persistent fragmentation between knowledge and action, and an interest in positioning design within these conditions as translational and situated practice.

1.2 Problem Statement

Marine environmental challenges are increasingly recognized as **complex and urgent**, yet the ways in which they are addressed remain largely **fragmented**. Scientific research, governance systems, economic sectors, and local communities often function within parallel but insufficiently connected frameworks (Ostrom, 2009).

Climate change and intensifying human pressures on marine ecosystems amplify this fragmentation: species distributions shift, ecological interactions reconfigure, and socio-economic systems face **increasing instability** (Gaines et al., 2023; IPCC, 2022). These transformations occur across scales and exceed the predictive capacity of linear management models.

Knowledge exchange research in marine science demonstrates that producing scientific evidence alone **does not guarantee implementation** or local adaptation (Cvitanovic et al., 2015). Barriers include **disciplinary silos**, institutional inertia, mismatched timescales, and limited collaborative structures.

As a result, many interventions struggle to engage with marine ecosystems in ways that are **context-sensitive, adaptable, and grounded** in real environmental conditions. The absence of **mediating practices** capable of operating across ecological, material, and social dimensions constrains the development of more responsive forms of environmental care.

1.3 Research Question

In marine contexts characterized by **ecological complexity and uncertainty**, **translating scientific knowledge** into situated and effective interventions remains challenging. While design is often positioned as a mediating practice between knowledge domains and local conditions, how this role can be enacted in practice under conditions of marine uncertainty remains insufficiently explored.

Research Question

How can design *operate as an experimental practice capable of mediating between* ***scientific knowledge*** *and* ***context-sensitive*** *practice under conditions of* ***marine uncertainty?***

1.4 Research Objectives

General objective

To develop and critically assess an **experimental design practice** capable of mediating between scientific knowledge and context-sensitive practice under conditions of **marine uncertainty.**

Specific objectives

- To **identify and frame** a marine species as a focus of study, examining ecological dynamics and vulnerabilities.
- To **define** a specific coastal site, analyzing environmental, institutional, and operational conditions.
- To **map** relevant actors and disciplines involved in the selected context, identifying opportunities for collaboration and knowledge exchange.
- To **develop** a design proposal that responds to the studied conditions as an exploratory contribution to ongoing environmental care practices.

1.5 Limitations

This research is shaped by structural limitations inherent to working within marine environments, living systems, and distributed collaboration.

First, **temporal misalignment**. Marine ecological processes unfold over extended and unpredictable timescales, whereas the thesis operates within a fixed academic timeframe. As a result, the ecological effects of the intervention extend beyond the temporal scope of this research.

Second, **environmental contingency**.Field-based restoration remains exposed to territorial and climatic unpredictability. Planned field installation was interrupted due to large-scale wildfires affecting the region during the scheduled deployment period, preventing in situ implementation and underscoring the vulnerability of restoration initiatives to external events beyond experimental control.

Third, **geographical distance.** The research was conducted across Italy and Chile, limiting continuous in situ observation and requiring mediated collaboration.

Finally, the study is **context-specific**, focusing on a single species within a defined coastal territory. Following Ostrom's SES framework (2009), findings are framed as situated contributions rather than universally generalizable models.



2. Context Framing

Kelp forests are selected in this research as a focal ecosystem due to their ecological centrality, socio-economic relevance, and increasing vulnerability, particularly along the Chilean coast where this study is geographically situated. As foundational marine systems, kelp forests structure temperate coastal environments through their three-dimensional habitats, high productivity, and regulatory functions. In Chile, they also sustain local livelihoods and coastal economies, while facing intensifying environmental and anthropogenic pressures.

This chapter frames the ecological, socio-economic, and environmental conditions that shape kelp forest systems, establishing the contextual foundations upon which the design research is situated.

Figure 3: Macrocystis pyrifera (giant kelp), a foundation species of temperate coastal ecosystems along the Chilean coast.
Photo: José Luis Kappes for Rewilding Chile.

2.1 The Ecological Role of Kelp Forest

The following sections examine kelp forests through interconnected ecological functions, highlighting the systemic conditions that inform subsequent design decisions.



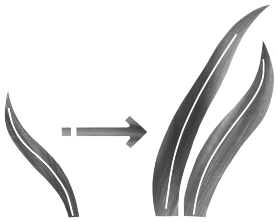
Hydrodynamic Regulation and Coastal Protection

Through their vertical canopies and dense holdfast networks, kelp forests modify water movement, light penetration, and sediment dynamics across nearshore gradients. By interacting directly with waves and currents, they reduce nearshore water motion and dissipate wave energy, acting as natural buffers that protect coastlines from erosion and mechanical stress (Burnett & Gaylord, 2022; Dayton, 1985; Rosman et al., 2010). This **attenuation of hydrodynamic forces** stabilizes sediments, moderates turbulence intensity, and reduces scouring at the seabed. The physical influence of kelp extends below the canopy, where decreased flow velocity creates more predictable mechanical conditions for benthic substrates (Gaylord et al., 2007). By modulating the transfer of kinetic energy across the water column, kelp forests contribute to **shoreline protection** and help maintain **geomorphological stability.** In contexts of intensifying storm regimes, this regulatory function becomes increasingly relevant for **coastal resilience.**



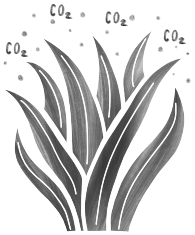
Habitat Provision and Biodiversity Support

The complex **three-dimensional architecture** of kelp forests creates habitat at multiple spatial scales. Their fronds, stipes, and holdfast structures provide shelter, feeding grounds, and nursery areas for a wide range of organisms, from microorganisms and epiphytes to invertebrates and fish. Many species depend on kelp forests at critical stages of their life cycles, relying on them for protection, reproduction, or access to food (Steneck et al., 2002; Teagle et al., 2017). The vertical stratification of the canopy increases **habitat heterogeneity**, supporting high levels of **species richness and functional diversity**, often exceeding those of surrounding unvegetated seabeds (Dayton, 1985; Graham et al., 2007). Beyond serving as passive habitat, kelp forests structure ecological interactions, shaping predator-prey dynamics and community composition. When these forests decline, the disruption extends beyond individual species, altering entire **trophic networks.**



Productivity and Biomass Export

Kelp forests are among the most productive marine ecosystems, rapidly converting sunlight and dissolved nutrients into organic matter (Steneck et al., 2002). This **high primary productivity** supports local food webs but is not confined to the forest itself. A substantial portion of kelp biomass becomes detached through natural breakage, grazing, or seasonal turnover. Transported by waves and currents, this organic material moves across the seascape, supplying food, energy, and detrital inputs to adjacent coastal habitats, offshore ecosystems, and even deep-sea environments (Filbee-Dexter et al., 2024; Krumhansl et al., 2016). Through this **spatial redistribution of biomass**, kelp forests function as **ecological connectors**, linking distant marine systems that would otherwise remain weakly coupled. Their productivity therefore operates not only locally but at **landscape scales**, reinforcing ecological interdependence across coastal regions.



Carbon Sequestration and Climate Regulation

The export of kelp-derived organic matter also reshapes discussions of marine carbon dynamics. For decades, kelp forests were overlooked in blue carbon frameworks because they do not accumulate carbon directly in sediments through root systems. However, recent research demonstrates that detached kelp biomass can be transported to deep or low-oxygen environments where carbon is effectively sequestered over longer timescales (Filbee-Dexter et al., 2024; Ortega et al., 2019). Beyond **long-term sequestration**, the movement of kelp-derived detritus across coastal and offshore zones contributes to broader **biogeochemical exchanges**, linking nearshore production with distant marine environments (Krumhansl et al., 2016). Recognizing this spatial redistribution reframes kelp forests as active regulators within **marine carbon pathways** rather than merely localized habitats.

2.2 The Socio-Economical Importance of Kelps in Chile

Historical Roots and the Expansion of Extraction

Along the Chilean coast, kelps are not only ecological foundation species but also **long-standing socio-economic resources.** Historically gathered from intertidal zones or collected after natural detachment, large brown seaweeds formed part of **coastal subsistence practices** and local ecological knowledge systems. These practices were embedded in seasonal rhythms, oceanographic variability, and community-based labor structures.

During the second half of the twentieth century, however, this relationship transformed. As international demand for alginates and seaweed-derived products expanded, Chile progressively integrated into global value chains of brown seaweed production (Buschmann et al., 2017; FAO, 2024). What had been a localized, relatively low-intensity activity evolved into a structured fishery with **export-oriented dynamics.** Vásquez (2008) documents how extractive pressure intensified after the 2000s, reshaping harvesting practices and **increasing dependence on brown seaweeds as a commercial commodity.**

Artisanal Fisheries and Coastal Livelihoods

Despite its insertion into international markets, kelp extraction in Chile remains primarily grounded in **small-scale and artisanal labor.** The brown seaweed fishery is largely carried out by **artisanal fishers operating in *caletas*** and remote coastal settlements (Vásquez, 2016). In many regions, kelp harvesting functions as a **complementary economic activity** supporting household incomes, particularly where alternative employment is limited. Beyond direct market value, kelp forests also provide **ecosystem services whose economic valuation exceeds the immediate price of extracted biomass.** As mentioned in Chapter 2.1, kelp ecosystems support a range of goods and services, including habitat provision, nutrient cycling, and coastal productivity, that sustain fisheries and local economies (Smale et al., 2013). Variability in recruitment, oceanographic conditions, and market prices directly affects coastal livelihoods, illustrating the tight coupling between ecological processes and socio-economic stability (Stotz, 2018).

Kelp at the Intersection of Ecology and Economy

Within this socio-economic context, kelps emerge as more than raw materials: they **sustain livelihoods**, structure coastal economies, and connect small-scale fishers to global industries. Yet their productivity and regeneration are **ecologically bounded**, dependent on oceanographic variability, recruitment cycles, and trophic dynamics. Framed as **socio-ecological systems** (Berkes et al., 2003), Chilean kelp fisheries operate at the intersection of environmental processes and human institutions. Governance transformations (Gelcich et al., 2010), co-management arrangements (Castilla & Fernandez, 1998), and recent management plans (SECOS, 2025; Vásquez et al., 2014) reflect attempts to navigate this intersection. In this sense, kelps in Chile function simultaneously as **ecological infrastructures** and **socio-economic stabilizers**, linking environmental resilience with the continuity of coastal livelihoods under conditions of **environmental uncertainty.**

Figure 4: Artisanal kelp harvesting along the Chilean coast, illustrating the small-scale extraction practices that sustain coastal livelihoods.
Photo: SUBPESCA Chile


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2.3 Environmental Threats Affecting Kelp Forests

Despite their ecological importance, kelp forests are increasingly threatened globally. Long-term analyses report declines in 38% of assessed ecoregions, with regional variability rather than uniform collapse (Krumhansl et al., 2016). These declines result from **interacting stressors across scales**, from climatic shifts to localized anthropogenic pressures (Smale et al., 2013).



Climate change and thermal extremes

Among global drivers, **ocean warming** stands out as one of the most pervasive and consequential threats to kelp forests. Kelp species are physiologically adapted to relatively narrow thermal ranges, and prolonged exposure to elevated temperatures can reduce growth, impair reproduction, and increase mortality (Smale et al., 2013).

Beyond gradual warming, extreme thermal events (particularly **marine heatwaves**) have emerged as critical tipping points. Over the past century, such events have become longer and more frequent (Oliver et al., 2018). These episodic disturbances can trigger abrupt **regime shifts**, replacing kelp-dominated systems with turf-forming algae or urchin barrens (Wernberg et al., 2016).

Once established, these alternative states may persist through **reinforcing feedbacks** that inhibit recovery, reshaping ecological structure and associated ecosystem services.



Ocean acidification and physiological stress

Changes in seawater chemistry represent an additional, more subtle stressor. **Ocean acidification** and altered carbonate chemistry influence macroalgal physiology and species interactions (Koch et al., 2013). While some macroalgae may exhibit short-term tolerance to elevated CO_2, responses are highly species-specific and context-dependent.

At the cellular level, carbon acquisition mechanisms shape **physiological responses** to changing carbonate conditions (Cornwall et al., 2017). Acidification rarely acts in isolation; it interacts with warming, nutrient regimes, and competition, potentially modifying community structure over time.

Rather than causing immediate collapse, these chemical stressors may **erode resilience**, increasing vulnerability to additional disturbances such as heatwaves or harvesting pressure.

Figure 5: Sea urchin proliferation affecting kelp structure, exemplifying how interacting stressors can destabilize kelp-dominated ecosystems.
Photo: Michael Langhans



2.3 Environmental Threats Affecting Kelp Forests

The particular case of Chile

While these threats affect kelp forests worldwide, the situation in Chile presents specific characteristics that intensify their impacts. The Chilean coastline hosts one of the largest distributions of kelp forests globally and is strongly influenced by the Humboldt Current System, which traditionally supports high productivity and buffers certain environmental stressors. However, this apparent resilience has obscured underlying **structural fragilities** linked to **intensified extraction** and **growing human pressure**, revealing vulnerabilities that are not immediately visible at the ecosystem surface (Vásquez et al., 2013).

Overharvesting has emerged as the most urgent and direct threat to Chilean kelp forests. Since the early 2000s, kelp extraction has increased sharply, driven by growing industrial demand for alginate and other kelp-derived products used in the pharmaceutical, cosmetic, and food industries. In several regions, **extraction rates exceed the natural regeneration capacity** of kelp populations, resulting in **long-term declines in forest structure and biomass** (Vásquez et al., 2013).

This rapid expansion of the brown seaweed fishery over recent decades has not always been accompanied by equivalent institutional capacity for monitoring and enforcement. As extraction intensified, management systems were required to adapt to increasing effort and spatial expansion (Buschmann et al., 2017; Vásquez, 2008). While the Chilean model of **co-management through TURFs (AMERB)** represents an internationally recognized governance innovation (Castilla & Fernandez, 1998; Gelcich et al., 2010), its effectiveness varies across regions and resource types. Differences in biomass and extraction pressure between managed and open-access areas suggest that **governance effectiveness, compliance variability, and regulatory enforcement capacity** directly influence resource condition (Vásquez, 2016). Brown seaweeds, distributed across extensive and heterogeneous coastal areas, present particular challenges for monitoring and control within this dynamic regulatory landscape.

Institutional reports further acknowledge the need to strengthen monitoring systems, improve compliance mechanisms, and refine administrative measures to ensure **long-term sustainability** (SECOS, 2025; SUBPESCA, 2018; Vásquez et al., 2014). These challenges reflect not the absence of regulation, but the difficulty of **aligning ecological variability, market demand, and institutional capacity** within a dynamic coastal system.

A critical distinction within harvesting practices further clarifies the severity of the problem. **Traditional artisanal collection methods**, based on gathering kelp that naturally detaches and washes ashore, allow for ecosystem regeneration and preserve habitat structure. In contrast, extractive techniques such as ***barreteo***, which **remove the entire kelp plant from its holdfast** using metal tools, eliminate the organism's capacity to regenerate and drastically alter benthic habitats (Saavedra et al., 2024). From a socio-ecological perspective (Berkes & Folke, 1998), these tensions illustrate the complexity of **governing renewable marine resources**, where extraction pressure, market incentives, ecological regeneration rates, and regulatory enforcement operate simultaneously across scales.



Figure 6: Schematic representation of *barreteo*, an extractive technique that removes the entire kelp holdfast, preventing regeneration and altering benthic habitat structure. Illustration: Marco Chemoli

2.3 Environmental Threats Affecting Kelp Forests

Ecological and coastal consequences

The cumulative effects of warming, acidification, and harvesting reshape not only species composition but the **structural and functional integrity** of kelp ecosystems. Following collapse events, kelp forests may shift toward **persistent degraded states** characterized by **reduced canopy complexity**, simplified trophic interactions, and lower biodiversity (Piñeiro-Corbeira et al., 2024; Wernberg et al., 2016).

The decline of kelp canopy reduces habitat availability for associated fish and invertebrate communities, altering food-web dynamics and weakening ecological connectivity (Smale et al., 2013). These structural simplifications compromise **ecosystem services** such as shoreline protection, nutrient cycling, and fisheries productivity, reinforcing the socio-ecological consequences of forest decline (Smale et al., 2019).

Importantly, long-term global analyses show that **recovery trajectories** are highly variable and often uncertain (Krumhansl et al., 2016; Wernberg et al., 2019). Where multiple stressors interact, recovery windows may narrow significantly, increasing the risk of **regime shifts** and **long-lasting ecological transformation.**

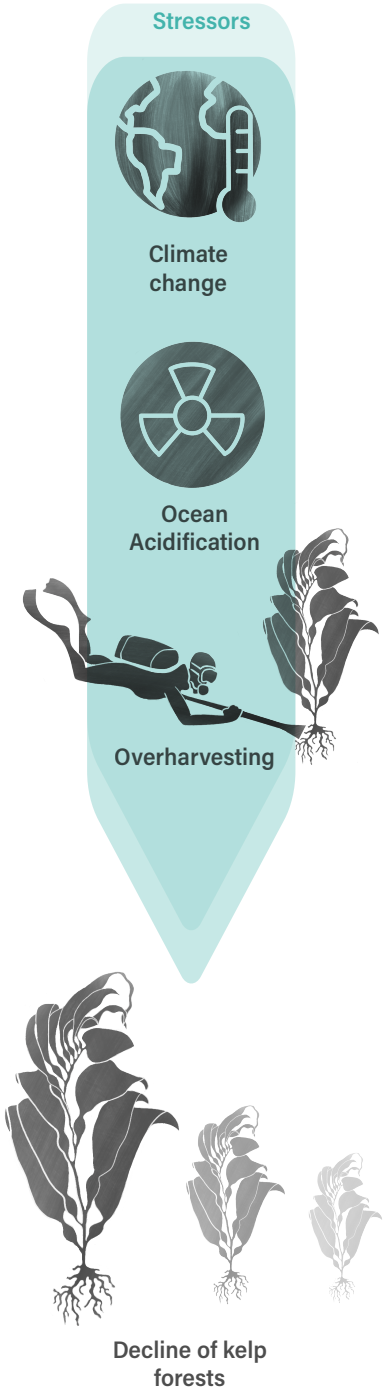


Figure 7: Interacting stressors contributing to kelp forest decline. Analytical diagram by author / Illustration: Marco Chemoli.

Figure 8: Contrasting kelp ecosystem states: complex, biodiverse forests (top) versus simplified benthic conditions after canopy loss (bottom). Photos: Kate Vylet; Stephen Connell.





2.4 Case Study: Coliumo, Bío-Bío Region

As discussed in the previous chapter, kelp forest degradation results from the interaction of **global drivers** and **locally mediated pressures**. Although these processes operate across scales, their ecological consequences vary significantly between territories (Krumhansl et al., 2016). Hydrodynamics, substrate composition, exposure regimes, and biological interactions shape context-specific patterns of recruitment, canopy persistence, and resilience (Smale et al., 2013).

For this reason, restoration cannot rely solely on generalized ecological models. Effective intervention requires engagement with the material, social, and operational conditions of a defined coastal system. A **situated case study** allows for the identification of locally actionable drivers, regenerative capacities, and institutional constraints shaping restoration feasibility.

Within this framework, Coliumo, located in the Bío-Bío Region of central-southern Chile, was selected as the case study site.

Criteria for Site Selection

Coliumo was selected based on three interrelated considerations:

- **Documented kelp forest decline.**
- **Persistence of ecological functionality suggesting regenerative potential.**
- **A defined governance and operational structure enabling controlled intervention.**

Together, these conditions position the site not as a collapsed ecosystem, but as a degraded yet viable socio-ecological system in which restoration efforts may produce measurable impact.

Documented Decline Linked to Extraction

According to local accounts and scientific observations, the bay of Coliumo once sustained extensive kelp forests that structured benthic habitats and underpinned local fisheries (Saavedra et al., 2024). Evidence indicates that **intensified macroalgae extraction** has been a particularly consequential factor in structural simplification of the forest and local canopy reduction. Historical increases in harvesting pressure coincide with measurable decreases in kelp coverage, alterations in benthic community composition, and the gradual displacement of fishing activities toward offshore zones (Saavedra et al., 2024; Vásquez et al., 2014).

While environmental variability remains relevant, extraction pressure in Coliumo represents a **territorially embedded and socially mediated driver** of ecological change. Unlike global climatic processes, harvesting operates within local governance and economic systems, making it analytically central to understanding the site's degradation trajectory.

Figure 9: Coliumo Bay, Bío-Bío Region, central-southern Chile. Coastal landscape of the selected case study site. Photo: González Sandoval

2.4 Case Study: Coliumo, Bío-Bío Region

Ecological Functionality and Regenerative Potential

Despite documented canopy loss, the system does not exhibit signs of **irreversible ecological collapse**. Scientific observations and local accounts indicate that remnant kelp individuals persist in the bay, and benthic habitats remain biologically productive (Saavedra et al., 2024). Hydrodynamic variability and substrate heterogeneity continue to structure ecological processes that support recruitment and growth.

These characteristics suggest that resilience has been reduced but not extinguished. Rather than confronting a fully transformed regime shift, restoration efforts in Coliumo engage with a **degraded yet functional socio-ecological system.** The persistence of ecological processes provides a basis upon which regeneration strategies may build, distinguishing the site from areas where structural recovery capacity has been entirely lost.

This coexistence of **degradation and regenerative potential** makes Coliumo an instructive context for restoration research.

Governance and Institutional Configuration

Coliumo is a coastal fishing community within the municipality of Tomé, whose local economy is primarily sustained by artisanal fisheries. Access to benthic marine resources in Chile is organized through **AMERBs (Áreas de Manejo y Explotación de Recursos Bentónicos)**, a **co-management system** granting collective rights of access, extraction, and stewardship over defined marine territories under state regulation (Castilla & Fernández, 1998; Gelcich et al., 2010).

AMERBs operate through internal governance mechanisms (including assemblies, elected leadership, surveillance duties, and reporting obligations to national authorities) structuring how resource use and management are conducted at the local level. This model has been internationally recognized as a governance innovation in small-scale fisheries (Gelcich et al., 2010).

Parallel to this collective system, aquaculture concessions constitute a distinct legal and operational framework established under the **Chilean General Fisheries and Aquaculture Law.** These concessions grant rights for specific cultivation activities within demarcated marine areas and are administered through separate regulatory procedures (SUBPESCA, nd). The coexistence of collectively managed extraction areas and individually granted aquaculture concessions defines the **institutional landscape** within which marine interventions must operate.

Understanding this governance configuration is essential for situating restoration initiatives within legally regulated and socially structured coastal territories.

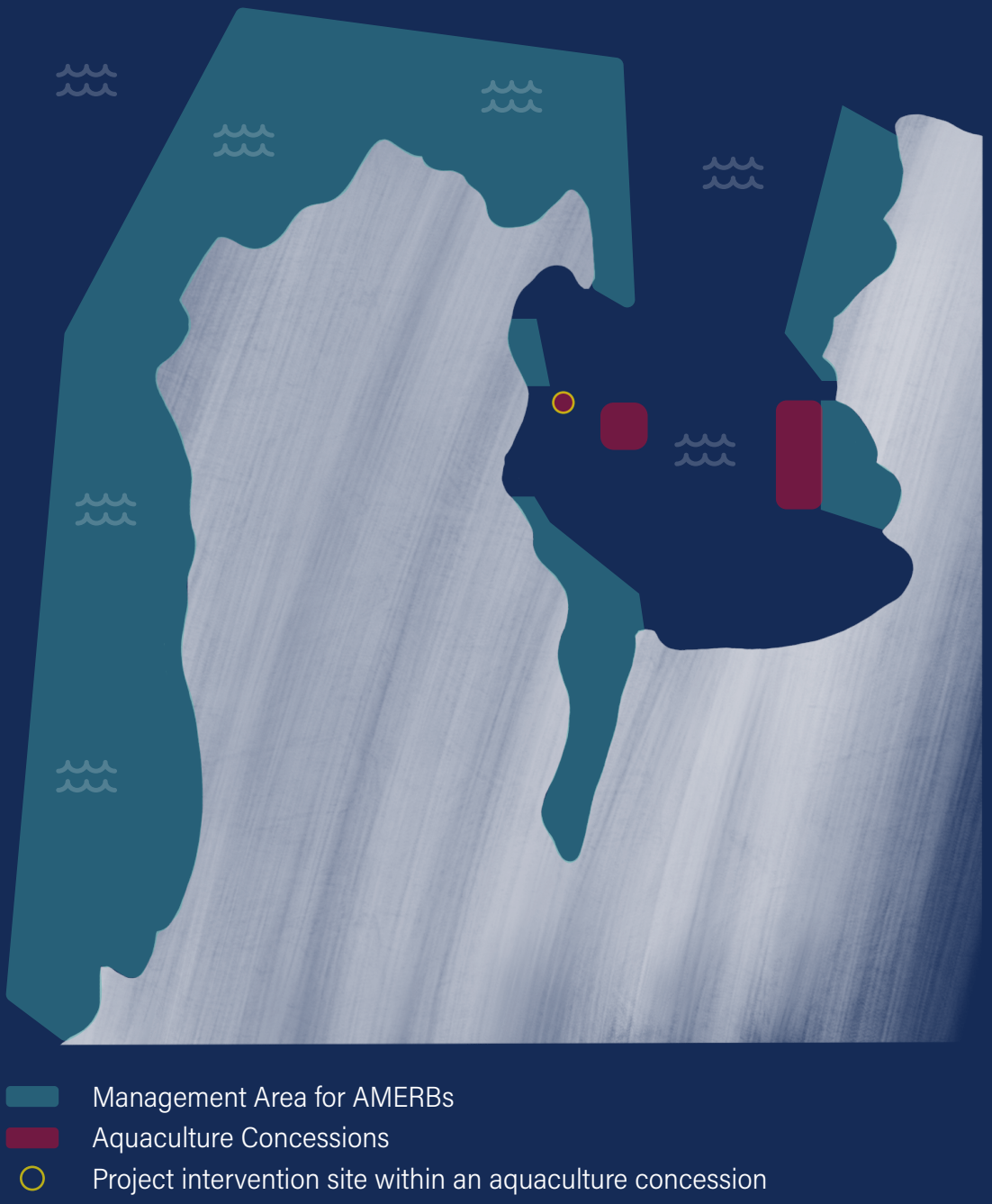


Figure 10: Management areas (AMERBs) and aquaculture concessions in Coliumo. The marker denotes the project intervention site within a concession area. Analytical diagram by author / Illustration: Marco Chemoli.

2.4 Case Study: Coliumo, Bío-Bío Region

Restoration trajectory: community and academic initiatives.

Coliumo has not been approached as a blank slate. Rather, it has been the site of prior and ongoing restoration initiatives that provide an empirical and institutional foundation for the present research. These experiences demonstrate both the regenerative potential of the bay and the technical, social, and logistical challenges involved in kelp restoration under real coastal conditions.

NGO Bosques de Huiro

The first documented restoration effort in Coliumo was led by the NGO Bosques de Huiro, which developed a **participatory pilot** involving local fishers, divers, educators, and community members. The initiative emphasized **knowledge co-production** and resulted in the publication of Guía para la restauración participativa de bosques de huiros, systematizing lessons learned (Saavedra et al., 2024). Although limited in scale, the project generated valuable insights into site preparation, attachment strategies, maintenance requirements, and the temporal commitment necessary for kelp establishment.

Beyond ecological outcomes, the initiative revealed critical **socio-operational dimensions**, including the need for long-term engagement, adaptive management under variable marine conditions, and coordination among diverse actors. It also reinforced local recognition of kelp as a foundational ecological structure requiring stewardship. At the same time, the pilot exposed constraints related to **fabrication methods, deployment logistics**, and the durability of support structures in dynamic environments.

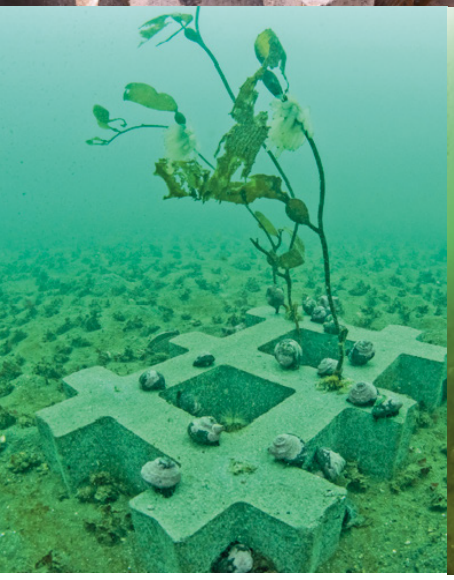
Universidad del Bío-Bío

Subsequently, researchers associated with the Universidad del Bío-Bío developed an applied research project exploring **design-mediated physical supports** for assisted kelp regeneration. Through **interdisciplinary collaboration** between marine biology and design, the initiative examined **prototyping strategies**, material configurations, and installation techniques in real coastal conditions. Particular attention was given to the interaction between structural form and hydrodynamic forces, as well as to the practical constraints of fabrication and deployment. Although experimental in scope, the project generated valuable knowledge regarding fabrication limitations, marine installation challenges, and the **operational feasibility** of design-driven restoration tools.

Together, these initiatives position Coliumo not as a collapsed ecosystem, but as a **degraded yet functional system** with documented regenerative efforts. They highlight both the feasibility and the limitations of prior restoration attempts, forming a **practical and conceptual foundation** upon which the present research builds.

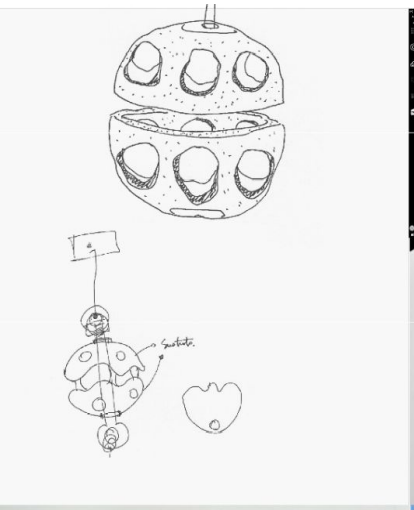
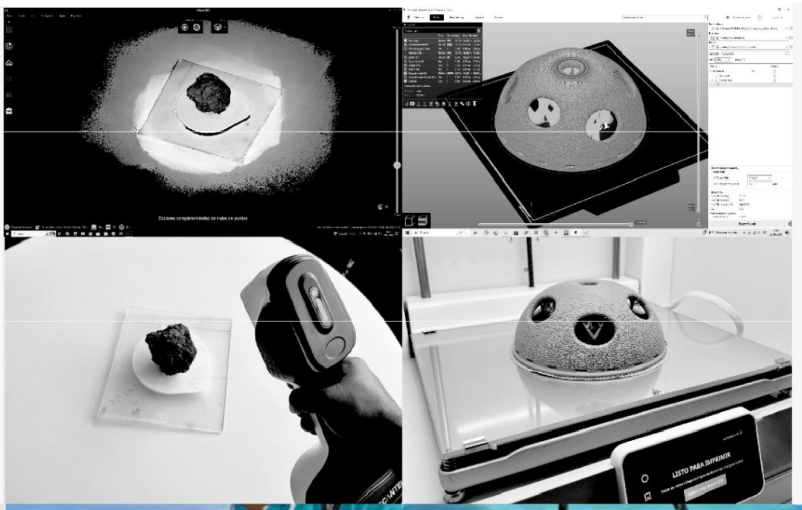
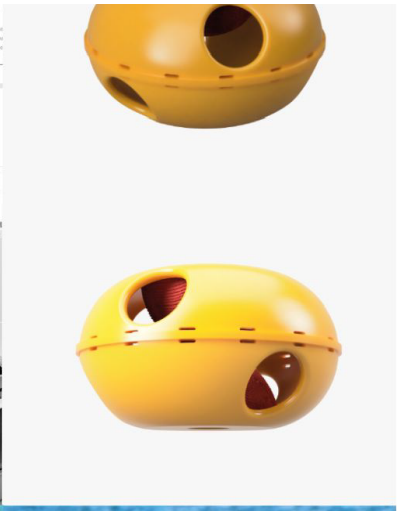
Figure 11: Coliumo restoration precedents: community-based participatory pilot by NGO Bosques de Huiro (top) and design-mediated prototyping and field validation by Universidad del Bío-Bío (bottom). Photos: Saavedra, 2024; images provided personally by Hernán Díaz.






▲ NGO Bosques de Huiro

▼ Universidad del Bío-Bío








2.5 Collaboration Configuration

The case study documents previous kelp forest restoration efforts in Coliumo while revealing an **existing network** of actors, knowledge, and infrastructure that directly informs the present research. The initiatives led by Bosques de Huiro and the Universidad del Bío-Bío establish the collaborative ground upon which this project is built. Rather than approaching Coliumo as an external observer, the research is embedded within an ongoing trajectory of restoration practices and engages directly with actors involved in earlier interventions.

Within this context, the project operates through a **configured collaboration** in which roles, expertise, and responsibilities are distributed across a small group of **key participants**. Understanding this configuration is essential to situating both the design process and the feasibility of the proposed intervention.

Roles and expertise within the collaboration

The research is led by the author as lead designer and design researcher, responsible for framing the research questions, defining the design strategy, and integrating ecological, material, and contextual constraints into a coherent design proposal. This role includes **mediating between disciplines**, translating biological requirements into design parameters, and guiding iterative prototyping.

Design expertise is supported by **Hernán Díaz and Gino Ormeño**, designers affiliated with the Universidad del Bío-Bío who participated in the earlier academic restoration project described in Section 2.4. Their experience provides continuity with previous **design-led experimentation** in Coliumo and contributes **practical knowledge** related to fabrication, installation, and operational constraints in marine environments.

Biological expertise is provided by **Luisa Saavedra** from the NGO Bosques de Huiro, whose role is to ensure the **ecological validity** of the intervention. Her contribution focuses on kelp life cycles, juvenile handling, transplantation timing, and the environmental conditions required for successful establishment.

A central operational partner in the project is **Jessica Cabrera**, who provides access to **existing marine infrastructure** within her aquaculture concessions in Coliumo (see Figure 11). This collaboration is coordinated through marine biologist Luisa Saavedra. Her infrastructure includes suspended lines with offshore buoys that can support the future installation and testing of the proposed system.
Her bivalve aquaculture facilities also host kelp juveniles, enabling access to **biological material** without relying on extractive collection from natural kelp forests.

- **Collaborators and partners:**

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- **Hernán Díaz & Gino Ormeño**
  Designers and academics at Universidad del Bío-Bío.
  Experience in design-led kelp restoration projects in Coliumo.

BOSQUES DE HUIROS

- **Luisa Saavedra**
  Marine Biologist.
  Biological and environmental feedback.
- **Jessica Cabrera**
  Marine farm concession holder, Coliumo.
  Provides access to aquaculture infrastructure for future system testing.

Collaborative dynamics and interdependencies

The collaboration is characterized by **strong interdependencies** between roles. Design decisions are informed by biological constraints, while biological actions depend on the availability of physical supports and marine infrastructure. Rather than operating through a linear structure, the collaboration functions through **iterative negotiation**, allowing the project to remain adaptive to ecological, logistical, and site-specific conditions. Importantly, this collaboration builds upon an existing network of actors already engaged in kelp restoration in Coliumo, reinforcing continuity and avoiding parallel or disconnected efforts.

2.6 Existing Care Practices for Kelp Forests

Conceptual Definitions
Understanding the conceptual and operational differences among existing kelp care strategies is essential for clearly defining the scope and contribution of this thesis. The following section outlines these distinctions.



Conservation and management-oriented approaches

Conservation represents the most established response to kelp forest decline and focuses on **reducing anthropogenic pressures** rather than actively intervening in ecosystem structure. In Chile, this approach has relied on spatial management tools such as marine protected areas, territorial use rights for fisheries, and regulations governing kelp harvesting (Vásquez, 2016). Long-term ecological research shows that, under controlled extraction, conservation can sustain adult biomass, recruitment cycles, and associated biodiversity (Dayton, 1985).

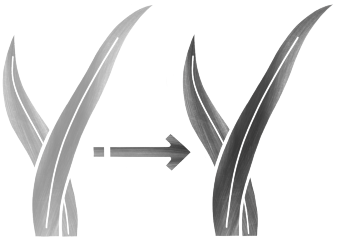
However, conservation assumes that **ecosystems retain sufficient resilience** to recover once pressures are reduced. Global syntheses indicate that cumulative stressors, including climate-driven regime shifts and marine heatwaves, can push systems beyond recovery thresholds even without direct exploitation (Krumhansl et al., 2016). Under these conditions, conservation becomes necessary but insufficient, as it does not actively address the loss of reproductive individuals, suitable substrate, or ecological feedbacks required for regeneration (Eger et al., 2022).



Ecological restoration and active interventions

Restoration strategies seek to **actively re-establish** kelp forests where natural recovery is limited or absent. These interventions are grounded in **ecological knowledge of kelp life cycles**, species interactions, and environmental constraints, and include stressor removal, kelp reintroduction, or habitat modification (Dayton, 1985; Vásquez & Buschmann, 1997). In practice, outcomes are highly uncertain, as recruitment success depends on context-specific interactions between physical conditions, biological processes, and stochastic events, making results difficult to generalize across sites (Smale et al., 2013).

Global reviews show that most restoration efforts remain small-scale, pilot-based, and resource-intensive, relying on **manual transplantation** and short-term monitoring, with scalability and long-term persistence unresolved (Eger et al., 2022). In Chile, participatory initiatives integrate local ecological knowledge and artisanal fishers (Saavedra et al., 2024), yet face constraints related to labor demands, coordination, and **limited technological transferability** (Oyarzo-Miranda et al., 2023).



Restocking and kelp transplantation



Cultivation and kelp farming

Restocking refers to the **reintroduction of kelp propagules, juveniles, or adults** into degraded areas, assuming absence reflects recruitment limitation rather than unsuitable conditions. Approaches include sporophyte transplantation and spore seeding on natural or artificial substrates (Vásquez & Buschmann, 1997).

Although restocking can generate short-term increases in kelp presence, **long-term effectiveness remains uncertain.** High mortality from hydrodynamic stress, grazing, or suboptimal substrates is common, and without addressing underlying drivers of decline, populations often fail to persist beyond initial establishment (Dayton, 1985; Smale et al., 2013). Reviews from Chile and globally highlight reliance on improvised anchoring systems, non-biodegradable materials, and intensive manual intervention, limiting ecological integration and scalability (Oyarzo-Miranda et al., 2023; Eger et al., 2022). These constraints make restocking difficult to apply as a standalone strategy in low-infrastructure contexts (Saavedra et al., 2024).

Kelp cultivation has primarily developed in response to **industrial demand** for biomass rather than as a restoration strategy (Vásquez, 2016). In Chile, farming has been explored to reduce pressure on natural beds and stabilize supply chains. However, cultivation systems are typically spatially decoupled from degraded kelp forests and **optimized for productivity** rather than ecological function.

While cultivated kelp may provide localized ecosystem services such as carbon uptake and nutrient cycling, these benefits are often temporary and **do not necessarily support wild forest recovery**, especially where genetic, ecological, or spatial mismatches occur (Ortega et al., 2019). Restoration literature emphasizes that engineering-oriented solutions do not automatically translate into ecological recovery unless designed to support habitat complexity and biodiversity (Jacob et al., 2018). As such, cultivation-focused strategies risk reducing kelp to its extractive value, overlooking its role as a foundational species within coastal ecosystems.

2.6 Existing Care Practices for Kelp Forests

Overview of existing strategies used in Chile

Along the Chilean coast, existing practices for kelp forest care emerge from **fisheries management, applied ecological research, and community-based initiatives**. Rather than forming a unified restoration model, these practices consist of situated responses shaped by local ecological conditions, governance frameworks, and socio-economic constraints (Saavedra et al., 2024; Santelices, 1989; Vásquez, 2016).

Despite more than two decades of experimentation, documented interventions remain spatially limited and technologically diverse (Oyarzo-Miranda et al., 2023). Current approaches largely fall within different forms of **restocking methods**, ranging from low-tech, in situ **transplantation** and simple anchoring systems to **laboratory-based strategies** grounded in controlled spore cultivation and incubation prior to outplanting.

This diversity reflects both contextual adaptability and **structural constraints**, which influence **scalability, material choices, and long-term viability.**

To further contextualize these dynamics, the following section examines selected kelp restoration initiatives in Chile identified in the review by Oyarzo-Miranda et al. (2023). These cases are analyzed in order to understand the technical approaches employed, their material and logistical requirements, and the extent to which they address (or reproduce) the structural limitations previously discussed.

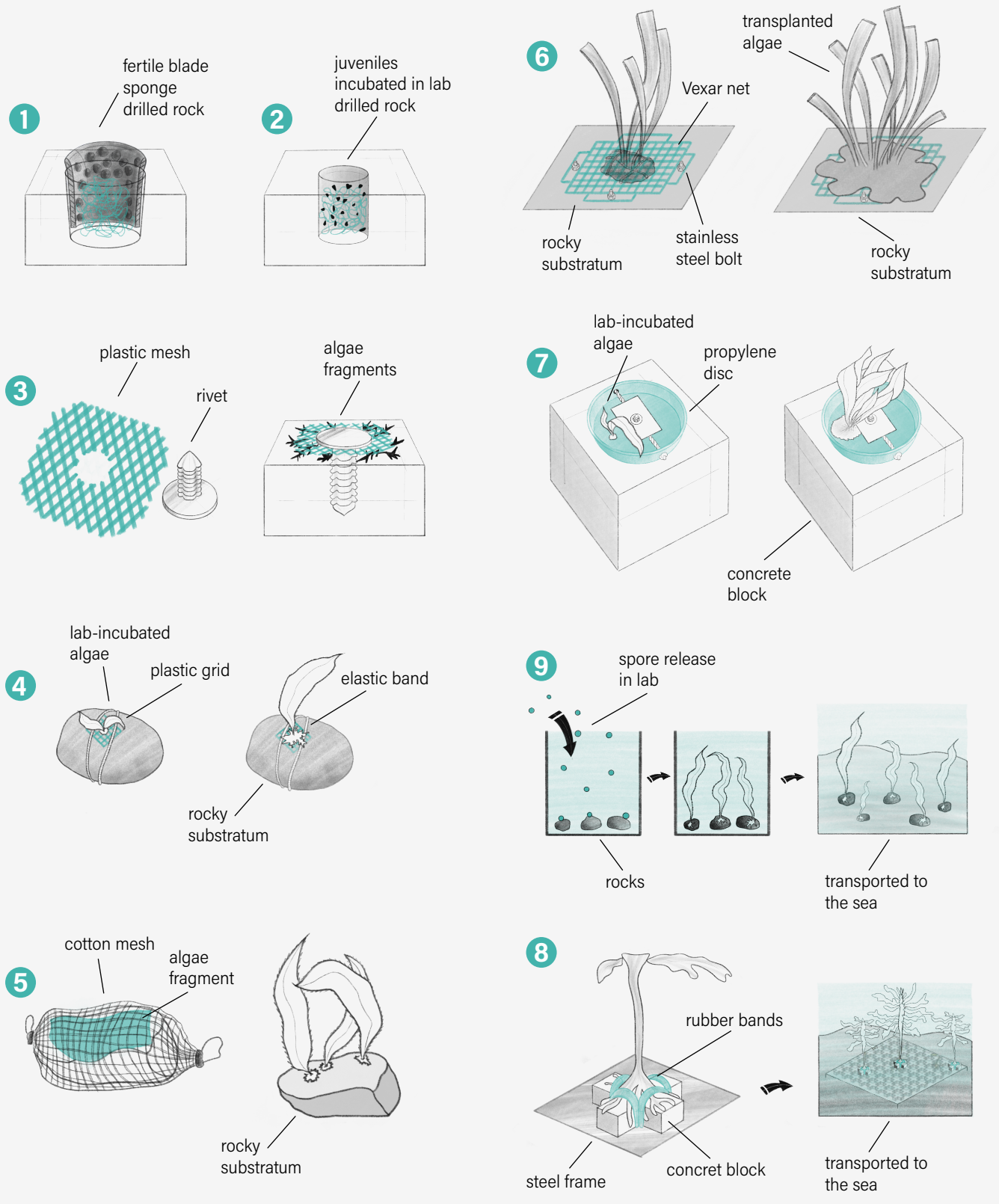


Figure 12. Representative methods of kelp restocking in Chile.
Illustration: Marco Chemoli, adapted from Oyarzo-Miranda et al. (2023).

2.6 Existing Care Practices for Kelp Forests

Table 1.
Diagnostic Matrix of Existing Kelp Restocking Approaches in Chile

Nº	Method	Biological Control	Ecological Mediation	Infrastructure Dependency	Intervention Logic
1	In situ spore release (drilled rock cavity)	Low	Medium	Low	Structural anchoring supporting natural recruitment
2	Ex situ incubation + transplant (drilled rock cavity)	High	Medium	High	Biological amplification via laboratory support
3	Fragment fixation (plastic mesh + rivet)	Medium	Low	Medium	Hardware-based structural stabilization
4	Ex situ incubation + temporary fixation (elastic band + grid)	High	Medium	High	Early-stage biological control with temporary fixation
5	In situ spore dispersal (cotton mesh wrapping boulder)	Low	Medium	Low	Low-tech assisted settlement
6	Transplanted algae secured mechanically (net + bolt anchoring)	Medium	Low	Medium	Mechanical fixation of mature individuals
7	Incubated juvenile on artificial substrate (disc + concrete block)	High	Medium	High	Engineered substrate with lab dependency
8	Direct transplantation (frame + bands)	Medium	Medium	Medium	Structural reinforcement of large individuals
9	Controlled ex situ spore seeding (natural attachment to rocks)	High	Medium	High	Lab-based recruitment with natural attachment

Scales

Biological Control
Degree of intervention over early life stages (recruitment, settlement, juvenile development).

- Low = Relies entirely on natural recruitment processes; no control over early development.
- Medium = Physical manipulation or transplantation of existing individuals; no ex situ cultivation.
- High = Active control of early life stages through incubation, seeding, or monitored ex situ growth.

Ecological Mediation
Extent to which the method addresses environmental stressors beyond fixation.

- Low = Structural fixation only; no mitigation of additional ecological stressors.
- Medium = Partial buffering of one environmental factor (e.g., flow stabilization or substrate selection).
- High = Integrated mediation of multiple environmental factors (biotic and/or abiotic).

Infrastructure Dependency
Level of technical, logistical, and material infrastructure required for deployment.

- High = Strong dependency on laboratory facilities, specialized equipment, or heavy hardware.
- Medium = Moderate logistical and technical requirements.
- Low = Low infrastructure demand; deployable in resource-constrained coastal contexts.

Comparative Diagnosis

The comparative matrix reveals a **structural polarization** in kelp restocking practices in Chile. Low-infrastructure approaches primarily rely on structural anchoring and natural recruitment, offering **limited biological control**. In contrast, laboratory-based methods enhance early-stage survival through controlled incubation or seeding, yet depend on **specialized facilities** and technical infrastructure.

Across cases, ecological mediation rarely extends beyond partial buffering of a single environmental factor, most commonly hydrodynamic stabilization. Broader stressors and multi-factor environmental variability remain largely unaddressed. As reflected in the matrix, no approach demonstrates **integrated ecological mediation** under low-infrastructure conditions.

This pattern highlights a persistent tension between **biological control and contextual feasibility**, suggesting the need to further examine how restoration systems might reconcile these dimensions across different scales and contexts.

2.6 Existing Care Practices for Kelp Forests

Overview of worldwide emerging and innovative approaches

Building on the structural diagnosis of Chilean restocking practices, it is necessary to situate these findings within a broader international landscape of **marine eco-engineering initiatives.**

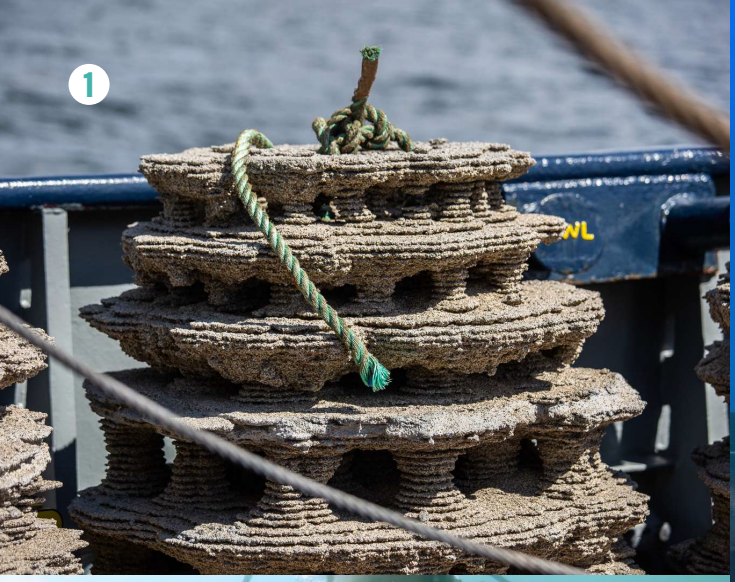
Beyond the Chilean context, experimental and technology-oriented approaches to marine ecosystem care have emerged globally within ecological engineering, artificial reef design, and habitat enhancement. Developed through research laboratories and interdisciplinary collaborations, these initiatives respond to the limitations of conventional restoration in marine environments shaped by artificial infrastructure and anthropogenic pressures (Dafforn et al., 2015; Firth et al., 2014; Strain et al., 2018).

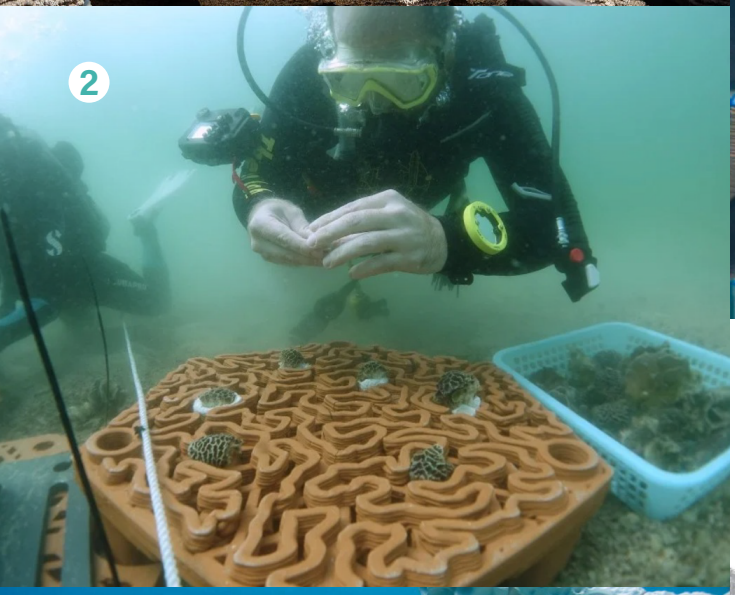
Rather than relying solely on transplantation, many projects explore **engineered substrates or modular systems** designed to enhance ecological performance. Prefabricated or additive-manufactured components are often used to introduce surface heterogeneity, porosity, and microtopographic variation, features associated with settlement processes and biodiversity patterns.

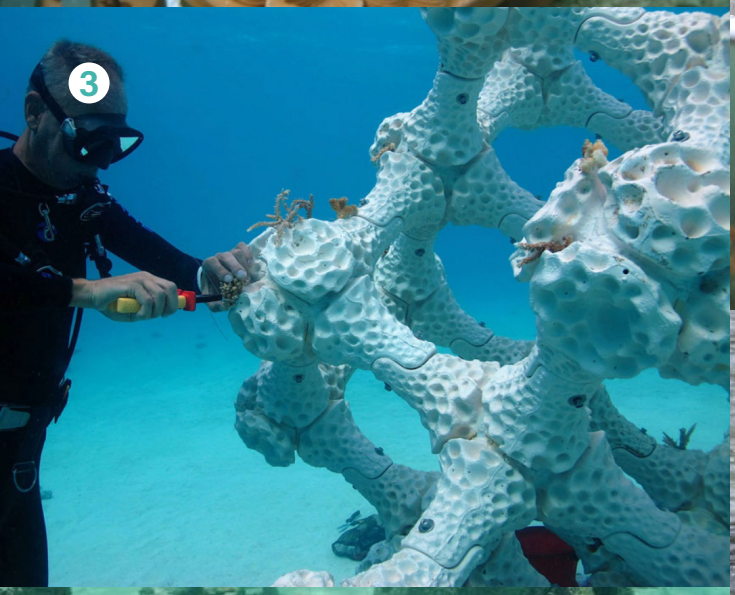
Within this broader landscape, **coral reef systems** have received substantial attention in design-led eco-engineering research, while temperate ecosystems such as **kelp forests** appear less prominently represented.

The following section examines selected international initiatives, focusing on their design strategies, fabrication logics, and resource configurations.

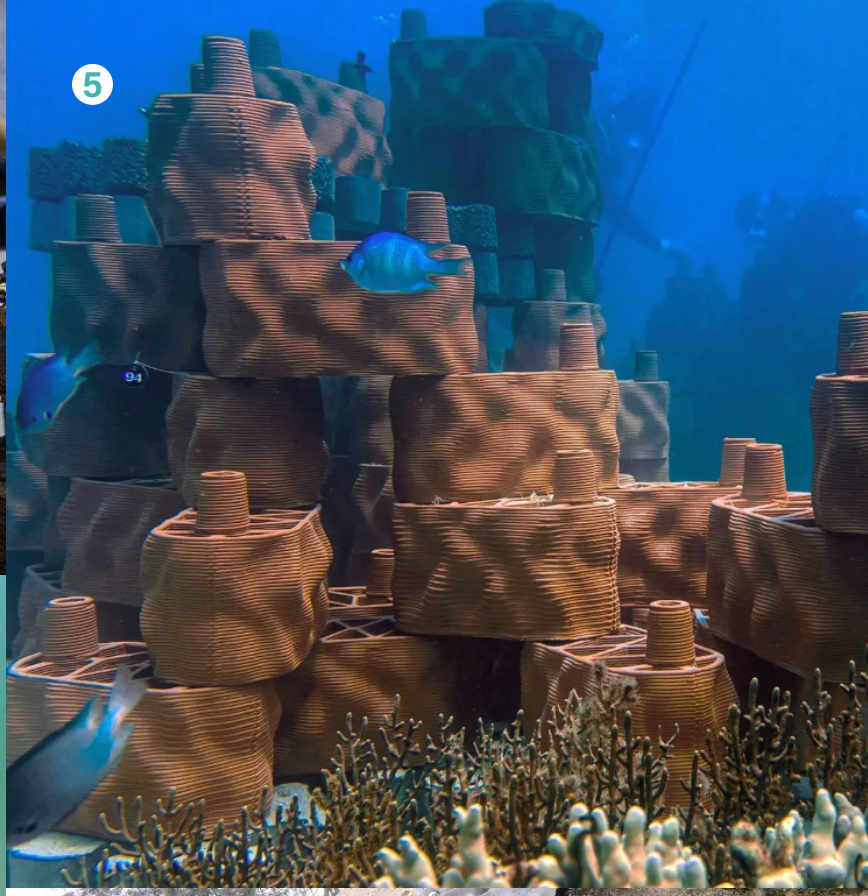
Figure 13: Worldwide examples of design-driven marine restoration initiatives.
Sources: (1) Ørsted; (2) Archireef; (3,6,7) ReefLab; (4) Reef Ball Foundation; (5) Rrreefs


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7

2.6 Existing Care Practices for Kelp Forests

Table 2.
Comparative Matrix of Design-Led Marine Eco-Engineering Initiatives

Nº	Project	Primary Ecosystem Focus	Design Strategy	Fabrication Logic	Resource Intensity
1	Ørsted	Fish and bivalve	Ecological modules integrated into energy infrastructure	Industrial prefabrication	High
2	Archireef	Coral reef	Microtopography optimization for larval settlement	3D-printed clay tiles	High
3	MARS (Reef Design Lab)	Coral reef	Modular porous interlocking units	Computational design + advanced casting	High
4	Reef Ball Foundation	Coral reef	Standardized hollow dome structures	Mold-based concrete casting	Medium
5	rrreefs	Coral reef	Geometry-optimized porous ceramic structures	Additive manufacturing (high-resolution)	High
6	Living Seawalls (Reef Design Lab)	Urban intertidal biodiversity	Retrofitted textured panels	CNC / prefabricated panels	Medium
7	EMU (Reef Design Lab)	Reef associated ecosystems	Biomimetic internal cavities and surface articulation	Parametric modeling + advanced fabrication	High

Scales

Resource Intensity
Degree of technical, economic, and infrastructural resources required for fabrication and deployment.

Low
- Local or low-tech fabrication possible
- Widely available materials
- Deployable without advanced computational tools
- Community-level implementation feasible

Medium
- Requires workshop or industrial-level fabrication
- Some computational or technical expertise required
- Partial dependence on external infrastructure

High
- Advanced computational design workflows
- Additive manufacturing or high-precision industrial fabrication
- Strong institutional or startup ecosystem required
- Limited accessibility outside high-resource contexts

Cross-Case Analytical Patterns

Ecosystem Bias
The majority of design-led eco-engineering initiatives focus on coral reef systems, positioning coral restoration as the dominant experimental field. Kelp forest restoration remains comparatively underrepresented.

Design Evolution
A clear progression is observable from standardized artificial reef typologies toward geometrically optimized, surface-driven, and biomimetic systems enabled by computational design and additive manufacturing.

Technological Dependency
As reflected in the predominance of high resource intensity classifications, most contemporary projects rely on advanced computational tools, additive manufacturing, or industrial-scale fabrication ecosystems.

Contextual Implication
This technological intensification suggests potential constraints for implementation in resource-constrained coastal contexts, highlighting the need for alternative material and deployment logics in temperate ecosystems such as kelp forests.

Together, these patterns indicate that design-led marine eco-engineering has advanced toward increasingly optimized and ecologically intentional systems, yet remains predominantly coral-focused and technologically intensive. This creates a gap in low-infrastructure contexts and in temperate ecosystems such as kelp forests, where restoration strategies require alternative material and deployment logics.

2.7 Opportunity Space for Design Intervention

The review of existing care practices for kelp forests reveals a landscape shaped more by contextual constraints than by **purpose-designed systems.** In Chile, interventions are implemented through management frameworks and community-led practices that rely on improvised tools, manual labor, and readily available materials. While these approaches respond pragmatically to local conditions, the tools and materials used are often not specifically designed for ecological care or long-term marine compatibility. In parallel, scientific research and restoration experiments are frequently conducted in academic or laboratory settings, generating valuable knowledge that is not always readily transferable to socially embedded, **low-infrastructure coastal contexts.**

At the global level, eco-engineering initiatives introduce more **intentional material and structural design** but remain dependent on advanced technical resources and institutional support. This contrast exposes a **translational gap** between locally grounded practices lacking purpose-designed tools and technologically sophisticated solutions that are difficult to adapt beyond pilot settings.

Within this gap, an opportunity arises to explore design as a way of engaging with **material and ecological interactions** without predefined outcomes. Rather than replacing existing practices, design can complement them through experimental and context-sensitive interventions that focus on material intention, environmental compatibility, and **adaptability under conditions of uncertainty.**

The design opportunity *lies in exploring how purpose-designed tools, materials, and structures can be developed to engage with* ***kelp forest restoration*** *under conditions of* ***ecological uncertainty, low infrastructure, and site-specific constraints.***



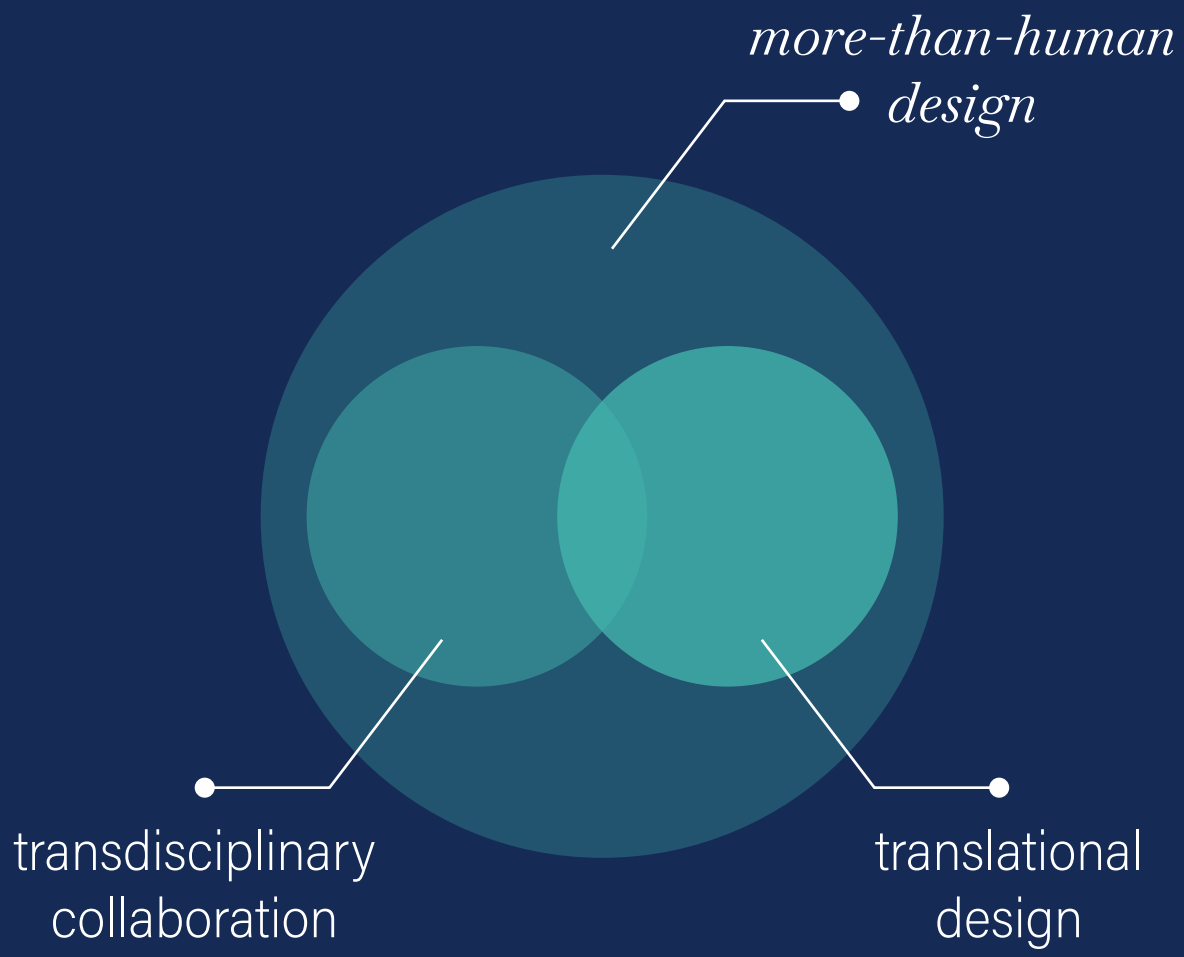


Figure 14: Diagram of the theoretical framework showing the relationship between more-than-human design, transdisciplinary collaboration, and translational design (author's own elaboration).

3. Theoretical Framework

This chapter establishes the theoretical foundations guiding the research. Following the diagnostic analysis of existing restoration practices, the project requires a conceptual framework capable of engaging ecological complexity, distributed agency, and cross-boundary collaboration. Rather than treating design as a neutral problem-solving tool, this framework positions it within relational ecologies and socio-technical systems.

The chapter unfolds across three interrelated dimensions: an ontological reframing of design beyond the human, an epistemological condition of transdisciplinary collaboration, and a methodological articulation of the designer's role as a translational actor. Together, these perspectives structure the research approach developed in the following chapters.

3.1 More-than-human Design

How does design shift when agency is no longer exclusively human?

The concept of the *more-than-human* emerges from a philosophical and ecological critique of human exceptionalism that later reshaped design theory. David Abram (2017) describes the Earth as a "more-than-human world," a living web of relations in which humans are only one among many participants. Bruno Latour (2004) and Jane Bennett (2010) further destabilize the modern separation between nature, culture, and matter, proposing instead a world composed of distributed agencies and interdependencies that exceed the human.

Within this ontological reframing, design is no longer understood as an external intervention imposed upon inert matter, but as a practice embedded within relational ecologies. Anne-Marie Willis (2006) conceptualizes this as ontological design: as humans design environments, those environments simultaneously configure human ways of being. Tony Fry (2008) foregrounds the ethical implications of this entanglement, arguing that every design decision conditions future possibilities of life, either sustaining or diminishing them. Design thus shifts from mastery and optimization toward responsibility, coexistence, and long-term care.

Posthuman and *more-than-human* perspectives within design research further articulate this shift. Ron Wakkary (2020) proposes a posthumanist epistemology in which agency emerges relationally and design knowledge is partial, situated, and continuously negotiated. Elisa Giaccardi and Johan Redström (2020) similarly frame *more-than-human design* as the maintenance of relations within assemblages of humans and nonhumans, where technologies are not neutral tools but co-actors shaping meaning, value, and interaction.

Kristina Lindström and Åsa Ståhl (2020) translate these ideas into situated practice through the notion of un/making, emphasizing listening, waiting, and at times undoing interventions to allow other agencies to surface. *More-than-human design* thus becomes a practice of attunement and responsiveness, attentive to temporalities, vulnerabilities, and ecological limits.

Recent scholarship demonstrates how these perspectives operate in practice. Nicenboim et al. (2024) argue that *more-than-human design* is increasingly defined by what it does in situated contexts, identifying modes such as making-with care and becoming-with multispecies. Poikolainen Rosén and Heitlinger (2025) discuss methodological challenges in including nonhuman perspectives and scaling such approaches. Expanding beyond Euro-American contexts, Design for More-Than-Human Futures (Tironi et al., 2023) frames design as worlding: a collective effort to sustain plural and fragile worlds.

More-than-human design establishes the ontological and ethical foundation of this research. It expands the field of participation beyond the human and repositions the designer within relational ecologies where agency is distributed and care becomes central.

- **RELATIONAL ECOLOGIES**
- **SHARED AGENCY**
- **MULTISPECIES COEXISTENCE**
- **DESIGN AS CARE**
- **ONTOLOGICAL ENTANGLEMENT**

3.2 Transdisciplinary Collaboration

How can complex more-than-human problems be addressed?

Socio-ecological challenges such as marine restoration cannot be framed as linear technical problems. (Rittel & Webber, 1973) describe such conditions as *wicked problems*: issues without definitive formulations, stable boundaries, or singular solutions. Their parameters shift as interventions unfold, and attempts at resolution transform the problem itself. When ecological systems are understood as *more-than-human* assemblages (where agency is distributed across species, materials, infrastructures, and institutions) complexity becomes structural rather than incidental.

Under these conditions, knowledge cannot remain confined within isolated disciplines. Funtowicz and Ravetz (1993) argue that in contexts of high uncertainty and high stakes, science enters a post-normal phase, where facts are uncertain, values are contested, and decisions exceed purely technical reasoning. Addressing such situations requires extended peer communities that incorporate diverse forms of expertise, including situated and non-academic knowledge.

This shift aligns with what Nowotny et al. (2003) describe as Mode 2 knowledge production: context-driven, socially distributed, and *transdisciplinary.* Knowledge emerges in application contexts through negotiation among heterogeneous actors rather than within stable disciplinary hierarchies. While interdisciplinarity restructures inquiry around shared problems (Klein, 1990), *transdisciplinarity* extends this restructuring beyond academia, integrating multiple levels of reality and forms of knowing (Nicolescu, 2002).

In socio-ecological systems, such integration is essential. Berkes et al. (2003) emphasize that resilience depends on adaptive governance, cross-scale interaction, and continuous learning across ecological and social domains. *Transdisciplinary collaboration* thus becomes the epistemological and organizational condition for engaging ecological uncertainty, distributed agency, and systemic interdependence.

Within this framework, complex more-than-human problems are addressed not through definitive solutions but through coordinated, adaptive, and iterative collaboration that bridges disciplines, institutions, communities, and ecological processes.

- **WICKED PROBLEMS**
- **SHARED RESPONSIBILITY**
- **KNOWLEDGE CO-PRODUCTION**
- **EXTENDED COMMUNITIES**
- **ADAPTIVE LEARNING**

3.3 Translational Design

What is the role of the designer in addressing complex more-than-human problems?

If *more-than-human design* establishes the ontological ground and *transdisciplinary collaboration* defines the epistemological condition, translational design specifies the methodological role of the designer within complex socio-ecological systems.

As environmental restoration engages multiple disciplines, institutions, communities, and nonhuman actors, linear models of knowledge transfer prove insufficient. *Translational design* reframes the designer not as a problem-solver applying predefined expertise, but as a mediator operating across heterogeneous domains of knowledge, material constraints, and ecological processes.

Star and Griesemer (1989) describe *translation* as a collective process through which actors with divergent goals coordinate work without full consensus, enabled by adaptable boundary objects. In this sense, the designer facilitates the creation of shared artifacts, prototypes, and material platforms that enable cooperation across disciplinary and institutional boundaries while preserving difference.

Actor-Network Theory further clarifies this role. Latour (2007) frames *translation* as the alignment and negotiation of interests within networks composed of human and nonhuman actors. Design interventions thus participate in the reconfiguration of relationships among scientists, communities, infrastructures, materials, and ecosystems. Knowledge does not circulate unchanged; it is transformed through materialization, negotiation, and situated experimentation.

Within design research, this *translational* capacity becomes central. Duarte, Anselmi, and Rognoli (2024) describe designers as *translational actors* who render knowledge accessible and actionable across domains. Lucy Suchman (2007) reinforces that action is always situated; knowledge emerges through engagement rather than prior abstraction. Ron Wakkary (2020) emphasizes relational and plural design epistemologies, while Manzini (2015) positions designers as facilitators within distributed networks of shared experimentation.

Together, these perspectives define *translational design* as the operational practice through which designers mediate, prototype, materialize, and reconfigure knowledge within complex ecologies. In this research, *translational design* structures experimental systems that enable interaction between marine science, material investigation, and kelp ecosystems under conditions of uncertainty and distributed agency.

- **TRANSLATIONAL ACTOR**
- **MEDIATION ACROSS ACTORS**
- **KNOWLEDGE RECONFIGURATION**
- **SITUATED EXPERIMENTATION**
- **NETWORK ALIGNMENT**



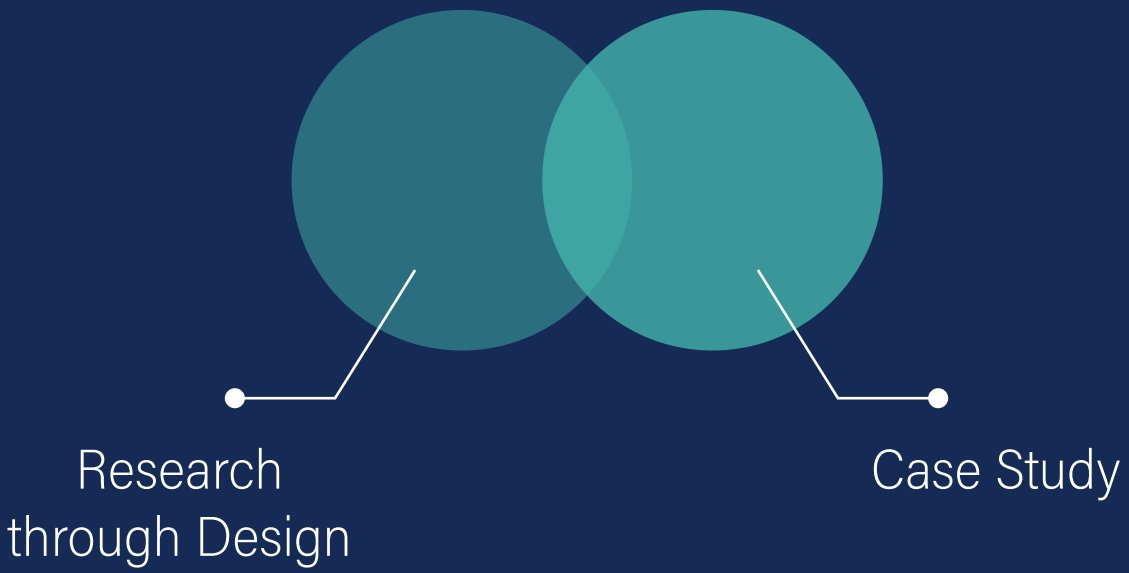


Figure 15: Diagram of the methodological framework, illustrating the integration of Research through Design and Case Study as complementary strategies structuring the empirical development of the research (author's own elaboration).

4. Methodological Approach

This chapter outlines the methodological framework guiding the empirical development of the research. Building upon the theoretical foundations established in Chapter 3, the study adopts a research design that operationalizes *more-than-human, transdisciplinary,* and *translational principles* in practice. The methodological approach combines *Research through Design* with a *case study* strategy, structuring how knowledge is generated, situated, and critically examined within the context of marine restoration.

4.1 Research through Design

This research adopts a *Research through Design* (RtD) approach as its primary methodological framework. RtD is particularly suited to complex, situated, and under-defined problems, where knowledge emerges through the act of designing rather than preceding it. Instead of applying pre-existing theories, RtD treats design practice itself as a mode of inquiry capable of producing original knowledge.

The foundations of this approach trace back to Christopher Frayling's (1993) distinction between research into, research for, and research through design. The latter emphasizes knowledge production through the making of artifacts, where processes, decisions, and outcomes become central vehicles for inquiry. This study aligns with this epistemic mode, positioning design activity as a generator of knowledge.

Within design research and Human-Computer Interaction, RtD has been further articulated in response to wicked problems that resist linear or predictive models. Zimmerman, Forlizzi, and Evenson (2007) describe RtD as enabling engagement with under-constrained problem spaces through artifacts that embody hypotheses, values, and possible futures. Such artifacts function not as final solutions but as exemplars that materialize questions and stimulate reflection and learning.

Similarly, Gaver (2012) argues that RtD produces annotated portfolios, conceptual insights, and transferable perspectives rather than generalizable scientific results. Knowledge is partial, situated, and contingent, yet valuable in uncertain contexts. This aligns with the objectives of this thesis, which seeks to generate situated understanding for marine restoration rather than definitive solutions.

RtD foregrounds iteration, reflection, and material engagement. Koskinen et al. (2013) emphasize that knowledge emerges through cycles of making, testing, and reframing in dialogue with real-world contexts. Prototypes and material experiments function as boundary objects mediating between theory, practice, and stakeholders, enabling insight through use, failure, and adaptation.

Reflective practice is central. Drawing on Schön's (1983) reflective practitioner, design is treated as an ongoing conversation with the situation, involving reflection in action and on action throughout the process.

Within this thesis, RtD provides a methodological structure for exploring ecological uncertainty, temporal dynamics, and multispecies interaction. Prototypes operate as research instruments that enable observation, negotiation, and adaptation over time. In doing so, RtD supports the more-than-human framework by allowing materials, organisms, and environments to shape inquiry, while operationalizing translational design across disciplinary and ecological boundaries.

- **KNOWLEDGE THROUGH MAKING**
- **ITERATIVE PROTOTYPING**
- **SITUATED INQUIRY**
- **REFLECTIVE PRACTICE**
- **DESIGN AS RESEARCH**

4.2 Case Study Approach

This research adopts a *case study approach* to investigate the situated dynamics of design-led marine restoration within a real-world context. A *case study* is particularly appropriate when the boundaries between a phenomenon and its context are not clearly defined, and when the aim is to understand how and why processes unfold rather than to measure frequency or predict outcomes.

According to Robert K. Yin (2009), *case study* research is suitable for examining contemporary phenomena in real-life settings, especially when the researcher has limited control over events and when multiple sources of evidence are involved. Rather than isolating variables, it enables in-depth exploration of complex interactions among actors, practices, and contextual conditions. This aligns with the objectives of this thesis, which examines design practice as it unfolds within ecological, social, and material constraints.

From a qualitative perspective, Sharan B. Merriam (2016) emphasizes that *case studies* are defined by their focus on a bounded system examined in depth. Their value lies in generating contextualized understanding through close engagement with the field. Instead of prioritizing representativeness, qualitative *case studies* foreground meaning, interpretation, and process, making them particularly relevant for research addressing situated practices and evolving conditions.

A common critique concerns limited generalizability. Bent Flyvbjerg (2006) challenges the assumption that valuable knowledge must be context-independent. He argues that context-dependent knowledge is central to learning and that carefully selected cases can significantly contribute to theory. Single cases may generate transferable insights through critical or paradigmatic examples and the testing of assumptions. The strength of the case study thus lies in its force of example rather than statistical generalization.

In this research, the *case study* is instrumental rather than representative. The selected case does not stand for all marine restoration contexts, but provides a situated ground for examining design practices, material experiments, and collaborative processes. Following Flyvbjerg, it functions as a site for learning through close engagement with specific conditions.

The approach aligns with the Research through Design framework outlined previously. As Yin (2009) notes, *case studies* are compatible with exploratory research, allowing iterative refinement of questions. Merriam (2016) further highlights their flexibility, enabling adaptation as new insights emerge. This is crucial in ecological contexts characterized by variability and uncertainty.

Within this thesis, the *case study* supports a holistic understanding of interactions between design, scientific knowledge, material systems, and *more-than-human* actors. By prioritizing depth over breadth, it enables the examination of design practice as a situated and evolving process, contributing to context-sensitive knowledge for marine restoration.

- **BOUNDED SYSTEM**
- **CONTEXT-DEPENDENT KNOWLEDGE**
- **IN-DEPTH ANALYSIS**
- **PROCESS-FOCUSED INQUIRY**
- **TRANSFERABLE INSIGHT**

5. Contextual Design Criteria

This chapter establishes the contextual foundation of the project by examining the biological requirements of *Macrocystis pyrifera*, the environmental dynamics of the intervention site in Coliumo Bay, and the socio-operational conditions shaping feasibility. Drawing from ecological literature, field observations, and prior restoration experiences, the chapter identifies critical constraints and opportunities. Rather than treating these as isolated factors, it frames them as interdependent parameters that collectively define the operative boundaries within which the design must function.

5.1 Biological Requirements of Macrocystis pyrifera

This project focuses specifically on *Macrocystis pyrifera,* the dominant kelp species in the case study context and the most studied within the research background of the collaborators. Understanding its biological requirements is essential to define the boundaries within which any design intervention aimed at kelp restoration can operate. Rather than attempting to control biological processes, this project acknowledges that the role of design is to create enabling conditions that align with the ecological needs and life dynamics of the species. The following section outlines the key biological requirements of *Macrocystis pyrifera* that directly inform the design constraints and opportunities of the proposed system.

Morphological Structure of the Sporophyte

Macrocystis pyrifera is a **large brown macroalga** whose morphology and life cycle directly inform its ecological behavior and restoration requirements. As one of the most widely distributed and ecologically dominant kelp species globally, it exhibits remarkable morphological and physiological plasticity across environmental gradients (Graham et al., 2007). Its complex structure enables **vertical growth** from the benthos to the water surface, forming **dense canopy forests** that structure entire coastal ecosystems. This architectural organization not only determines its capacity for attachment, buoyancy, and light capture, but also influences its mechanical interaction with hydrodynamic forces and substrate conditions, factors that are critical when considering assisted restoration strategies.

The macroscopic individual that forms kelp forests corresponds to the diploid sporophyte stage (2n). This structure is composed of three primary anatomical components:

Holdfast: a complex, root-like structure that anchors the alga to hard substrates. Its primary function is mechanical attachment rather than nutrient absorption.

Stipe: a flexible, elongated axis that connects the holdfast to the photosynthetic structures. It contributes to mechanical flexibility and vertical extension.

Blades (laminae): flattened, photosynthetic fronds attached along the stipe, often associated with pneumatocysts.

Pneumatocysts: gas-filled bladders located at the base of the blades that provide buoyancy. These structures maintain vertical orientation in the water column by elevating the photosynthetic tissues toward the surface, optimizing light capture and influencing canopy formation dynamics.

Thallus: the entire vegetative body of the alga including Holdfast, Stipe, Blades and Pneumatocysts.

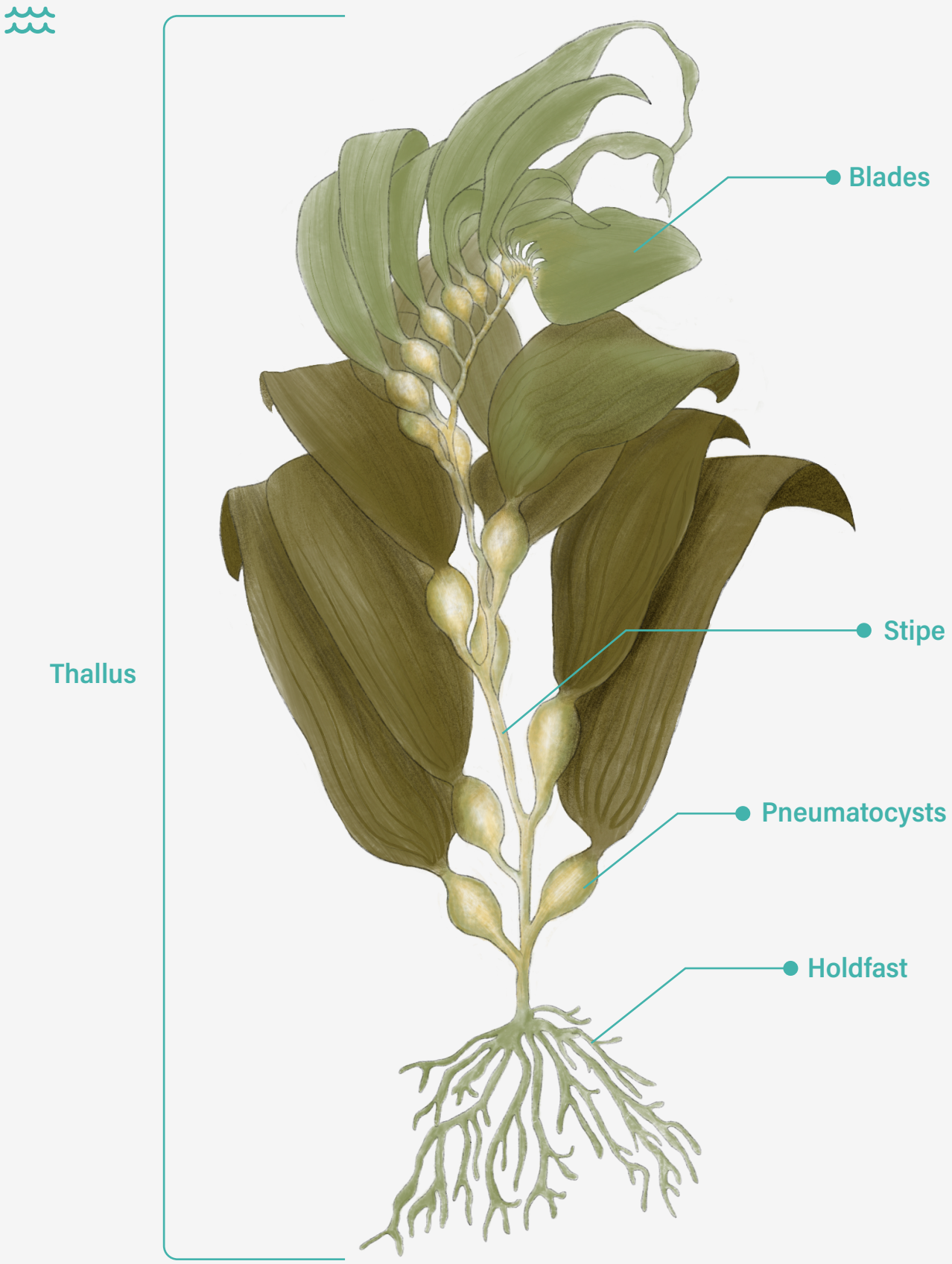


Figure 16: Morphological structure of Macrocystis pyrifera (sporophyte stage), illustrating its primary anatomical components: holdfast, stipe, blades, and pneumatocysts. Illustration: Marco Chemoli

5.1 Biological Requirements of Macrocystis pyrifera

Life Cycle of Macrocystis pyrifera

This project focuses on the **juvenile sporophyte** stage of *Macrocystis pyrifera* (2n), as early establishment represents a critical bottleneck for forest recovery. To understand this vulnerability, it is necessary to briefly outline the species' life cycle.

Macrocystis pyrifera exhibits a heteromorphic alternation of generations, meaning that it alternates between **two morphologically different life stages.** The large, visible kelp that forms underwater forests corresponds to the diploid sporophyte (2n), the canopy-forming structure commonly associated with kelp ecosystems.

This adult sporophyte produces haploid zoospores (n) through meiosis. Zoospores are microscopic, mobile **reproductive cells** that are released into the water column and transported by currents. At this stage, survival depends entirely on chance encounters with **suitable environmental conditions.**

For development to continue, these zoospores must settle onto a **stable and compatible substrate**, attach successfully, and germinate into microscopic male and female gametophytes (n). These gametophytes are invisible to the naked eye and highly sensitive to environmental stress. After fertilization between male and female gametophytes, a new diploid sporophyte (2n) forms. This early sporophyte (initially just a few millimeters in size) must survive mechanical stress, grazing, and environmental variability in order to grow into the canopy-forming adult.

For restoration purposes, the most critical stages occur at the microscopic and juvenile phases. Spore settlement, gametophyte development, and early sporophyte establishment are **highly sensitive** to substrate stability, light availability, hydrodynamic exposure, and nutrient conditions (Dayton, 1985; Reed et al., 2000; Schiel & Foster, 2006). Mortality rates are high, and successful recruitment depends on short temporal "windows" in which environmental conditions align.

Rather than being continuous, kelp recruitment is episodic and contingent. This introduces intrinsic uncertainty into population dynamics and highlights the importance of physical structures capable of supporting **early attachment**, reducing mechanical stress, and enabling the transition from microscopic stages to self-sustaining juveniles.

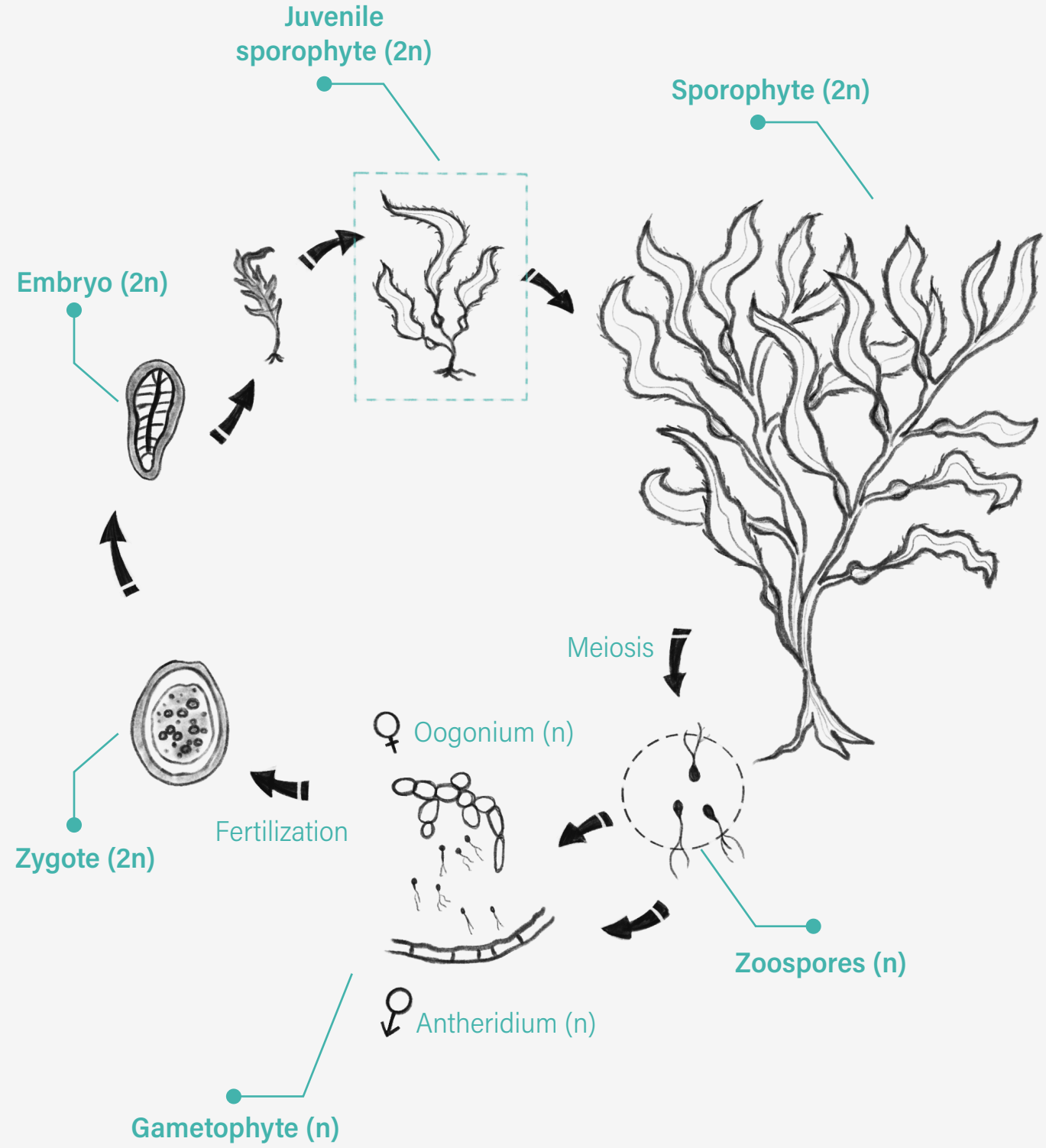


Figure 17: Representation of the life cycle of Macrocystis pyrifera.
Illustration: Marco Chemoli, adapted from Guía para la restauración participativa de bosques de huiros (Saavedra et al., 2024).

5.1 Biological Requirements of Macrocystis pyrifera

Growth Dynamics and Temporal Uncertainty

Growth in *Macrocystis* is characterized by **rapid vertical extension** under favorable conditions; however, this growth is neither linear nor predictable. Environmental variability, disturbance regimes, and biological interactions shape survival probabilities at each stage (Dayton, 1985; Graham et al., 2007).

Importantly, *Macrocystis* sporophytes display **high plasticity** in growth rates and canopy development across latitudinal and environmental gradients (Graham et al., 2007). Yet despite this plasticity, juvenile stages remain **mechanically vulnerable. Hydrodynamic forces** scale non-linearly with organism size and projected area, and **wave-induced drag** increases the probability of dislodgement as thallus size increases (Gaylord et al., 1994). This interaction between morphology and water motion imposes structural constraints on early establishment and subsequent size-dependent survival.

Field observations conducted during this research further indicate that early holdfast development exhibits a **pyramidal expansion** pattern, increasing its basal footprint at a faster rate than the radial thickening of the stipe. While the stipe primarily elongates vertically, the holdfast expands to **improve anchorage**. This differential growth pattern highlights the species' strategy of prioritizing attachment stability before vertical biomass accumulation.

This establish a fundamental constraint for design: kelp growth cannot be accelerated or standardized. Any intervention must accommodate long and uncertain biological timelines.

Substrate Requirements and Attachment

Substrate instability, sedimentation, and scour are particularly detrimental during early life stages, often leading to high mortality among spores, gametophytes, and juvenile sporophytes (Dayton, 1985). Experimental evidence demonstrates that even moderate sediment deposition can drastically reduce post-settlement survival and attachment success in habitat-forming seaweeds (Schiel & Foster, 2006).

Successful recruitment requires not only the presence of hard substrate but also sufficient **texture complexity** and stability to allow holdfast development and progressive anchoring. In natural rocky environments, surface irregularities **enhance distributed attachment** and resistance to dislodgement, while smooth surfaces are associated with weaker fixation (Milligan & DeWreede, 2000; Westermeier et al., 2010).

From a design standpoint, **substrate stability**, roughness, resistance to burial, and controlled surface complexity emerge as critical parameters for restoration-oriented interventions.

Figure 18: Underwater view of Macrocystis pyrifera showing the expanded holdfast anchoring to rocky substrate. The triangular overlay highlights the basal footprint growth and distributed attachment. Photo: Phillip Colla for Ocean Light



5.1 Biological Requirements of Macrocystis pyrifera

Light Availability and Depth

Light availability is one of the primary limiting factors for Macrocystis pyrifera growth and distribution. Photosynthetic performance is strongly influenced by depth, water clarity, and canopy shading. Microscopic stages exhibit defined irradiance thresholds for successful gametogenesis and sporophyte development (Dayton, 1985; Graham et al., 2007).

Variability in solar insolation across latitudes further shapes growth dynamics and vertical distribution limits (Graham et al., 2007). **Suspended sediments and turbidity** reduce irradiance, potentially constraining recruitment windows.

Although *Macrocystis* exhibits physiological plasticity in pigment composition and growth responses under variable light conditions, excessive enclosure, shading, or positioning within high-turbidity boundary layers **may alter irradiance** conditions below thresholds required for juvenile establishment.

Water Motion, Nutrients, and Physiological Exchange

Water motion plays a central role in the physiology of *Macrocystis pyrifera*. Nutrient uptake occurs across thallus surface, with blades functioning as the principal sites of **nutrient assimilation and carbon fixation.**

Under low-flow conditions, a thicker diffusive boundary layer forms around blade surfaces, limiting nutrient replenishment at the tissue interface. **Increased turbulence** reduces this boundary layer, enhancing nutrient exchange and metabolic performance (Buschmann et al., 2004; Hurd, 2000).

However, hydrodynamic forces simultaneously generate drag and acceleration forces that scale with thallus size and shape (Gaylord et al., 1994). Thus, water motion exerts a dual influence: facilitating nutrient exchange while imposing **mechanical stress.**

The holdfast primarily serves an anchoring function rather than a dominant absorptive role (Dayton, 1985), indicating that flow conditions at blade level are disproportionately significant compared to basal regions. Consequently, while hydrodynamic exposure must be understood as a source of nutrient delivery at the blades level, it should be also understood as a mechanical stress for the holdfast attachment.

Implications for Design

Taken together, these biological characteristics establish operative boundaries within which any intervention must function. Recruitment limitation, substrate stability, sediment sensitivity, light thresholds, hydrodynamic exchange, and size-dependent mechanical stress are not isolated variables but interdependent ecological conditions.

Rather than prescribing specific outcomes, these constraints define the ecological field within which design decisions are subsequently articulated. Any restoration-oriented structure must therefore **negotiate stability and exposure, protection and exchange, enclosure and openness**, in alignment with the multiphase and plastic life cycle of *Macrocystis pyrifera.*

Figure 19: Submerged canopy of Macrocystis pyrifera illustrating vertical extension toward light
Photo: Abbey Dias for Bull Kelp



5.2 Environmental Conditions of the Site

The intervention site is located in **Coliumo Bay**, within the municipality of Tomé, Región del Biobío, Chile. The experimental systems are situated in the **shallow subtidal zone**, a permanently submerged environment structured primarily by hydrodynamic forces, light attenuation, sediment mobility, and benthic interactions (Dayton, 1985).

This coastal sector forms part of the temperate southeastern Pacific and is shaped by the interaction between semi-protected bay waters and exposure to open-ocean swell. Coliumo's geomorphological configuration generates spatial variability in wave exposure depending on orientation and seasonal wind patterns.

Hydrodynamic Regime and Seasonal Forcing

Field observations confirm **persistent water movement** even under moderate sea states. In shallow areas, oscillatory surge associated with wave action generates drag and acceleration forces that scale with organism size and projected area (Gaylord et al., 1994). These forces structure benthic communities and influence the mechanical survivorship of attached organisms.

Winter storm systems intensify near-bed orbital velocities, increase **sediment resuspension**, and reduce safe operational windows for underwater intervention (Dayton, 1985). Spring and summer conditions are comparatively calmer, yet water motion remains a defining environmental constant rather than an episodic disturbance. Hydrodynamic forcing also **regulates nutrient flux** and boundary layer thickness at organism surfaces, linking mechanical exposure to physiological performance (Hurd, 2000).

Substrate Heterogeneity and Sediment Dynamics

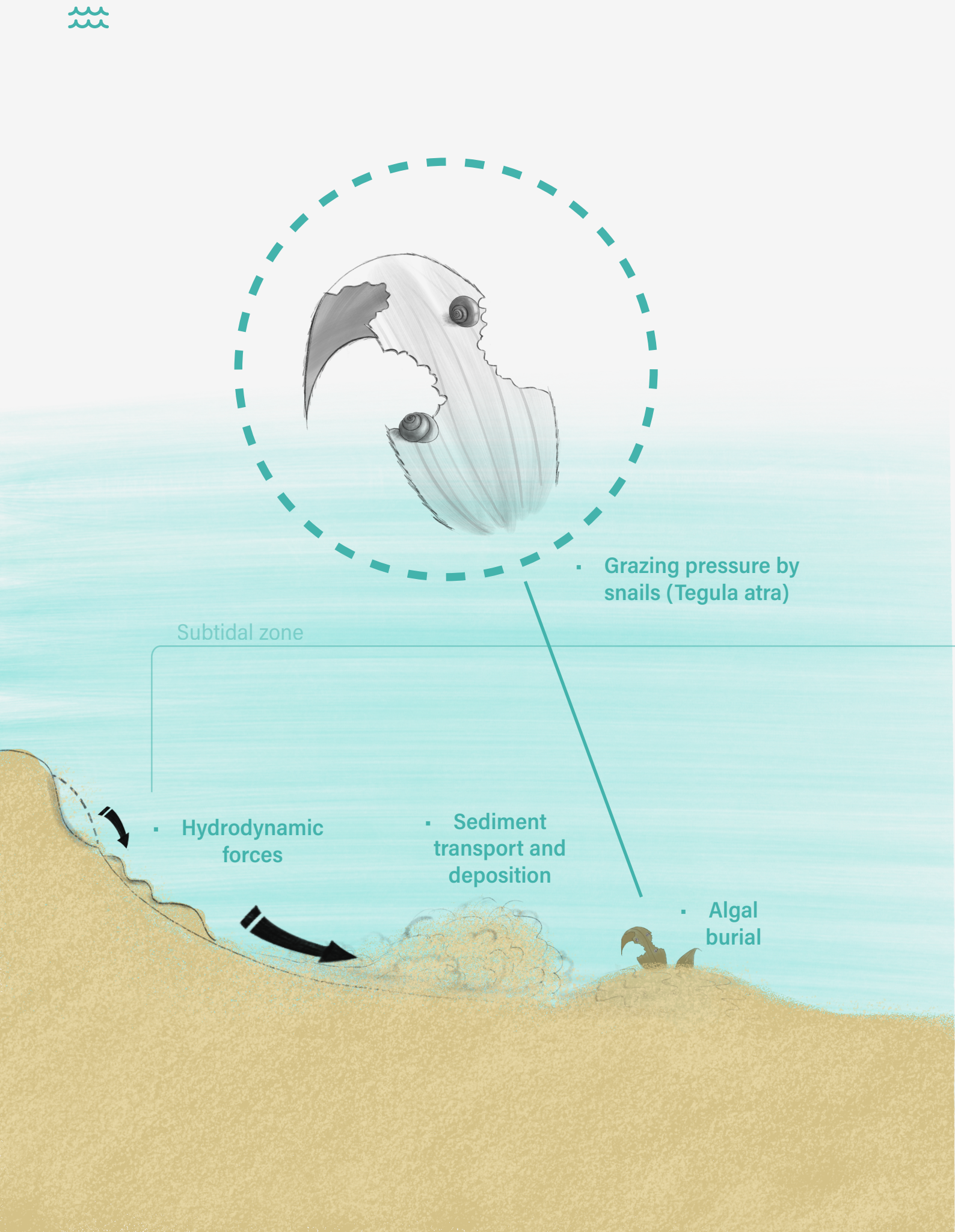
The seabed presents heterogeneous conditions where **consolidated rocky** outcrops coexist with sandy and partially **sediment-covered sections**. This variability occurs over short spatial scales and cannot be assumed static.

Field inspections revealed that rocky substrates may become **intermittently buried** following high-energy events. Sediment mobility continuously reconfigures microtopography, generating alternating cycles of burial and exposure. Restoration guidelines for Chilean kelp forests emphasize the need for preliminary site prospection under such variable substrate conditions (Saavedra et al., 2024).

Benthic Interactions and Grazing Pressure

The site supports **active benthic communities**, including **grazing invertebrates** such as Tegula atra, commonly associated with rocky temperate Chilean coasts. Herbivory is a recognized structuring factor in kelp-dominated systems (Dayton, 1985), and in Chilean subtidal environments, herbivore–kelp interactions influence recruitment dynamics and localized canopy structure (Vásquez & Buschmann, 1997).

Figure 20: Schematic representation of environmental conditions in the subtidal zone of Coliumo Bay, illustrating hydrodynamic forces, sediment transport and burial, and grazing pressure. Illustration: Marco Chemoli


· Grazing pressure by snails (Tegula atra)
Subtidal zone
· Hydrodynamic forces
· Sediment transport and deposition
· Algal burial

5.3 Socio-Operational Context

The intervention site in Coliumo operates within a socio-ecological system shaped by artisanal fisheries governance, small-scale aquaculture infrastructure, and limited technological capacity. Understanding this configuration is essential not only from a governance perspective, but as a determinant of practical design feasibility.

Territorial Governance Structure

Coliumo's coastal waters are regulated primarily through AMERB (Áreas de Manejo y Explotación de Recursos Bentónicos), a co-management regime that grants organized artisanal fishers exclusive territorial rights over benthic resources (Gelcich et al., 2010; SUBPESCA, n.d.). This governance structure defines access, extraction, and intervention possibilities within the coastal system.

However, the present intervention is not deployed within an AMERB territory. Instead, it is situated within an **existing aquaculture concession of bivalves.**

This distinction is critical. While AMERBs operate under collective governance structures that require internal agreement and are oriented toward resource extraction management, aquaculture concessions provide a legally defined and **operationally controlled marine space.** By situating the experimental intervention within this concession, the project avoids interfering with collectively managed fishing areas and reduces administrative complexity associated with collective decision-making processes.

Operational Infrastructure and Embeddedness

The aquaculture concession functions as the primary operational interface for the intervention.

The concession provides:

- **Physical anchoring points** through suspended cultivation lines and buoy systems
- **Logistical access** for installation and periodic monitoring
- **A real hydrodynamic environment** representative of local marine exposure
- **Access to biological material** for transplantation without relying on extractive collection from natural kelp forests

This embeddedness directly shapes design constraints since installation must be compatible with existing suspended systems.

Low-Infrastructure Restoration Conditions

Unlike restoration programs conducted in high-technology research contexts, restoration efforts in Coliumo operate under modest logistical conditions. Access to advanced underwater robotics, automated monitoring systems, or industrial marine fabrication facilities is limited.

Deployment relies primarily on:

- **Diver-based manual installation**
- **Small-scale boats**
- **Basic fastening tools**
- **Locally available materials**

These conditions fundamentally influence scale, complexity, and material selection.

Figure 21: Aquaculture concession infrastructure in Coliumo Bay, showing suspended buoy lines that define the low-infrastructure, embedded operational context of the intervention. Photos: Guía para la restauración participativa de bosques de huiros (Saavedra et al., 2024).




TUMO





5.4 Practice-Based Insights from Prior Kelp Restoration Efforts

Beyond the biological, environmental, and socio-operational conditions outlined in Sections 5.1–5.3, further structural understanding emerged through literature and semi-structured interviews with practitioners involved in kelp restoration initiatives in Chile. This practitioner-based perspective complements formal literature by revealing operational and mechanical nuances not always explicitly documented in scientific publications.

Early-Stage Mechanical Vulnerability

Field-based insights reinforced the pattern of **recurrent detachment** events during the first weeks following transplantation. These failures often occurred before holdfast structures had fully regenerated or expanded, suggesting that the establishment phase constitutes a **temporally vulnerable window** in which biological development and environmental forces remain imbalanced.

Stabilization in kelp restoration must therefore be understood as a temporal process rather than a static condition. Juvenile individuals initially require **external mechanical support**; however, as stipes elongate and holdfasts expand, load distribution and hydrodynamic interaction change. Practitioner accounts emphasized that fixation systems that remain rigid over time may fail to accommodate tissue growth. Mechanisms effective during immediate deployment may become **structurally mismatched** as biological expansion progresses.

Vertical Positioning: Sediment Interaction, and Grazing Exposure

Pilot restoration initiatives conducted by the *Universidad del Bío-Bío* in Coliumo implemented suspended modules positioned above the seabed rather than resting directly on it. Field-based observations indicated that elevating the structures **reduced exposure to mobile sediments**, which frequently reconfigure benthic microtopography following high-energy events.

By remaining suspended, the modules avoided burial and localized scour while also **limiting direct interaction with benthic grazers** such as Tegula atra, commonly observed on rocky substrates in the area. These observations suggest that vertical positioning modifies sediment contact, grazing pressure, and local light conditions, influencing early-stage establishment beyond purely mechanical stability.

However, suspension alone did not guarantee performance. *Macrocystis pyrifera*, commonly referred to as "huiro flotador" (literally, "floating kelp"), exhibits intrinsic buoyancy due to its gas-filled pneumatocysts. During early establishment, before the holdfast generates sufficient anchoring force, upward lift can destabilize vertical orientation. Adequate module mass was therefore necessary to **counteract buoyancy and maintain vertical tension.**

Figure 22: Intrinsic buoyancy of Macrocystis pyrifera (top) and rigid fixation systems (bottom), illustrating tensions between flotation and anchorage. Photos: Guía para la restauración participativa de bosques de huiros (Saavedra et al., 2024); Vital Kelp

5.4 Practice-Based Insights from Prior Kelp Restoration Efforts

Geometry, Substrate Interaction, and Attachment

Attachment ecology studies demonstrate stronger fixation of juvenile kelp on irregular rocky substrates compared to smooth surfaces (Milligan & DeWreede, 2000). Microtopographic variability increases contact area, enhances frictional resistance, and reduces slippage under wave exposure.

Holdfast regeneration frequently occurs around **protrusions and grooves**, increasing resistance to dislodgement through distributed anchoring (Milligan & DeWreede, 2000). Observations of juvenile *Macrocystis* and *Lessonia* in natural environments show early establishment within **crevices and structural relief**, where haptera orient along available geometry and gain partial protection from drag (Westermeier et al., 2010).

Field observation indicate that artificial surfaces exhibiting highly articulated surface textures often show **improved attachment performance** in early *Macrocystis* stages. These observations suggest that beyond material hardness, the geometry and scale of surface roughness play a decisive role in facilitating holdfast establishment.

Marine-Compatible Materiality

Given prolonged exposure to seawater and the ecological sensitivity of the site, material selection constitutes a structural and ethical constraint. Marine infrastructure frequently introduces synthetic components that may persist beyond their functional lifespan or generate unintended ecological impacts.

Within this research, materiality is treated as an integral design parameter guided by the following principles:

- **Resistance to saltwater degradation**
- **Absence of toxic leachates**
- **Structural durability**
- **Compatibility with ecological restoration objectives**

Material selection is therefore framed not only as a structural decision, but as a responsibility within marine systems characterized by long temporal scales and ecological interdependence.



5.5 Translation into Design Criteria

The preceding sections defined the biological constraints of Macrocystis pyrifera, the environmental dynamics of Coliumo Bay, and the socio-operational conditions shaping intervention feasibility. Building on these contextual and practice-based insights, this section synthesizes them into explicit design criteria.

Rather than prescribing a finalized configuration, the aim is to delineate the feasible design space through a set of operative principles. These criteria remain directly traceable to the findings presented in Sections 5.1–5.4.

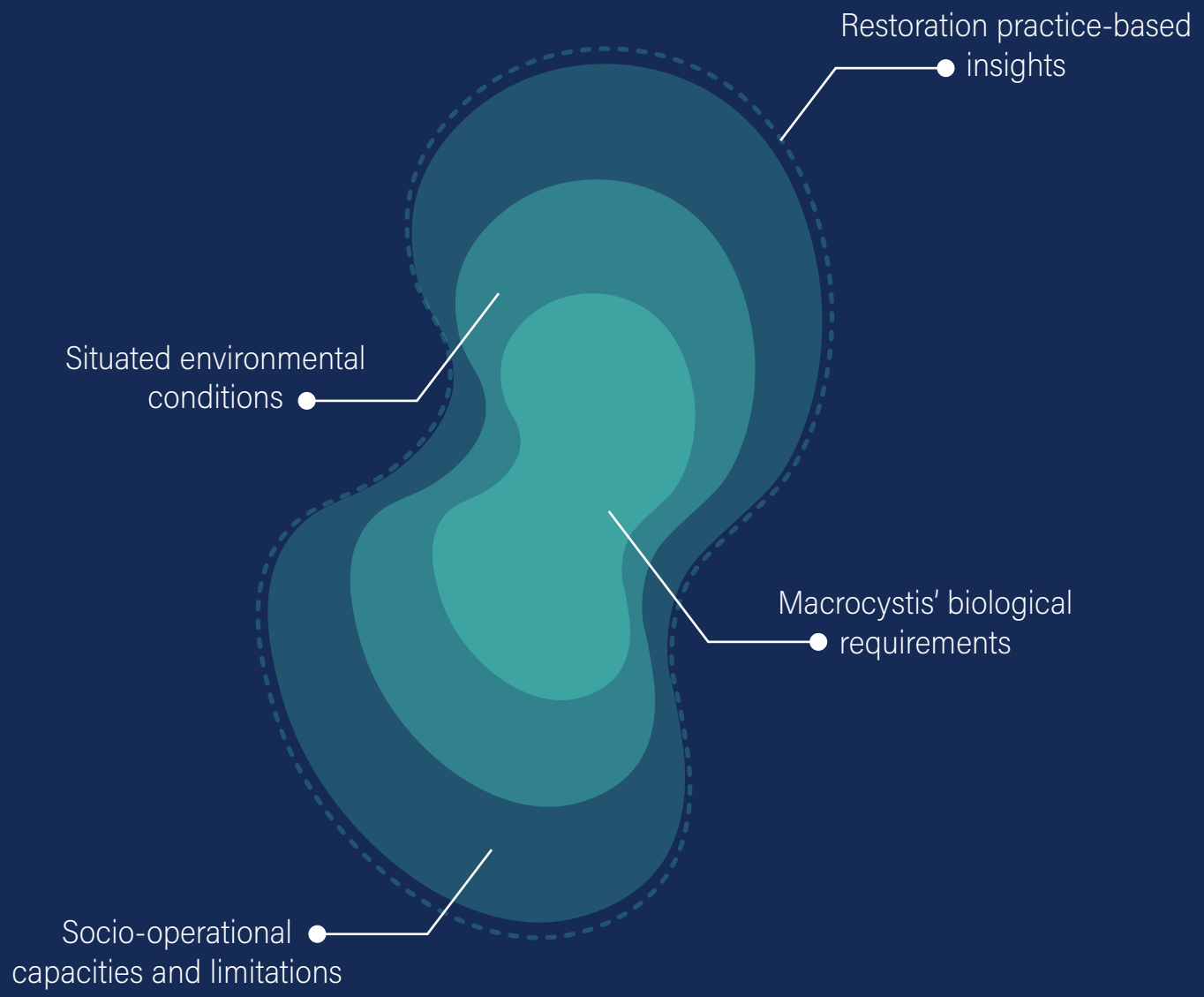


Figure 23: Conceptual synthesis linking biological requirements, situated environmental conditions, socio-operational constraints, and practice-based insights into an integrated design space for intervention (author's own elaboration).

Table 3.
Situated Conditions and Derived Criteria

Contextual Domain	Identified Constraint or Phenomenon	Translated Design Requirement
Biological	Mechanical instability before holdfast consolidation	**Provide temporary structural stabilization that does not inhibit biological expansion**
Biological	Complex textured surfaces enhance distributed attachment	**Integrate multi-scalar surface differentiation to facilitate progressive holdfast development**
Environmental	Scour and burial of seabed-level elements	**Mitigate direct sediment interaction through spatial positioning strategies**
Environmental	Localized herbivory pressure at substrate level	**Consider vertical separation to reduce direct grazing exposure**
Environmental	Reduced light availability negatively affects algal growth	**Maintain exposure to ambient light conditions appropriate to shallow depth regimes**
Practice-based	Upward buoyant force due to gas-filled pneumatocysts	**Incorporate sufficient mass to counteract buoyancy and maintain vertical tension**
Biological	Limited hydrodynamic flow constrains nutrient exchange	**Ensure hydrodynamic flow at the blade-level**
Socio-ecological	Limited technical equipment and specialized operational capacity	**Enable manual deployment and structural simplicity**
Practice-based	Long-term environmental exposure and ecological sensitivity	**Prioritize marine-appropriate and durable materials**
Socio-ecological	Limited access to advanced materials, fabrication technologies, and supply chains	**Favor locally accessible materials and low-complexity fabrication processes**

6. Concept Development

This chapter translates the contextual criteria established in the previous chapter into a structured process of concept development. Rather than pursuing a fixed solution, this phase explores how a restoration system can operate under biological uncertainty, early-stage mechanical vulnerability, and site-specific constraints. Biological uncertainty is reframed as a design parameter, leading to the formulation of controlled experimental configurations (C1–C4) that enable systematic observation of kelp–structure interaction.

6.1 Design Intention

This project is positioned within an **active ecological restoration framework** aimed at facilitating the regeneration of *Macrocystis pyrifera* in Coliumo by intervening in a critical bottleneck of recovery: the **structural vulnerability of early-stage establishment.**

Following historical overextraction in Coliumo, kelp forests have not naturally reconstituted, despite the presence of opportunistic juveniles associated with suspended aquaculture infrastructure. This suggests that recruitment capacity persists, yet mechanical and environmental constraints prevent the transition from isolated individuals to stable benthic populations.

The proposal addresses this limitation through an **assisted transplantation system that integrates temporary structural support**, aiming to establish viable reproductive clusters capable of reinforcing natural regeneration processes.

This approach is viable within Coliumo's current context, where natural rocky substrates remain available, oceanographic conditions are comparatively stable, and recent participatory initiatives indicate growing local awareness toward kelp conservation.

While site-specific, the system is conceived as modular and **adaptable to comparable coastal environments** facing similar early-stage establishment constraints.

6.2 Consolidated Design Principles

Based on the analytical mapping presented in Table 2, the following operative framework articulates the strategic principles guiding the development of the system. These principles do not describe isolated technical requirements, but define the structural logic through which the intervention engages with biological growth, environmental forces, and socio-ecological conditions.

- Ecological–Biological Principles

1. Designing for Biological Temporality
The system must operate within non-linear ecological timeframes. Rather than imposing fixed stabilization, it must accommodate growth-dependent transformations, recognizing that attachment, structural consolidation, and resilience emerge progressively.

2. Multi-Scalar Anchoring Logic
The interface must articulate differentiated structural scales: micro (surface roughness), meso (crevices), and macro (curved geometries), to approximate the anchoring conditions observed in natural and restorative environments.

3. Blade-Level Nutrient Exposure
The system must allow sustained flow at blade level to support nutrient exchange and metabolic functioning, avoiding configurations that generate excessive shielding.

4. Performance-Oriented Spatial Positioning
Positioning within the water column is treated as a performance variable.
Vertical separation mediates sediment burial, grazing pressure, and light availability, influencing early-stage establishment conditions.

5. Vertical Forest Structuring
Structure must emerge from a calibrated balance between gravitational mass and the intrinsic buoyancy from Macrocystis through sufficient counterweight to maintain vertical tension.

- Installation and Monitoring Logic

6. Operational Autonomy
The system must function within low-infrastructure conditions.
Compactness, manual deployability, and independence from specialized operators or advanced technical equipment are integral performance parameters rather than secondary constraints.

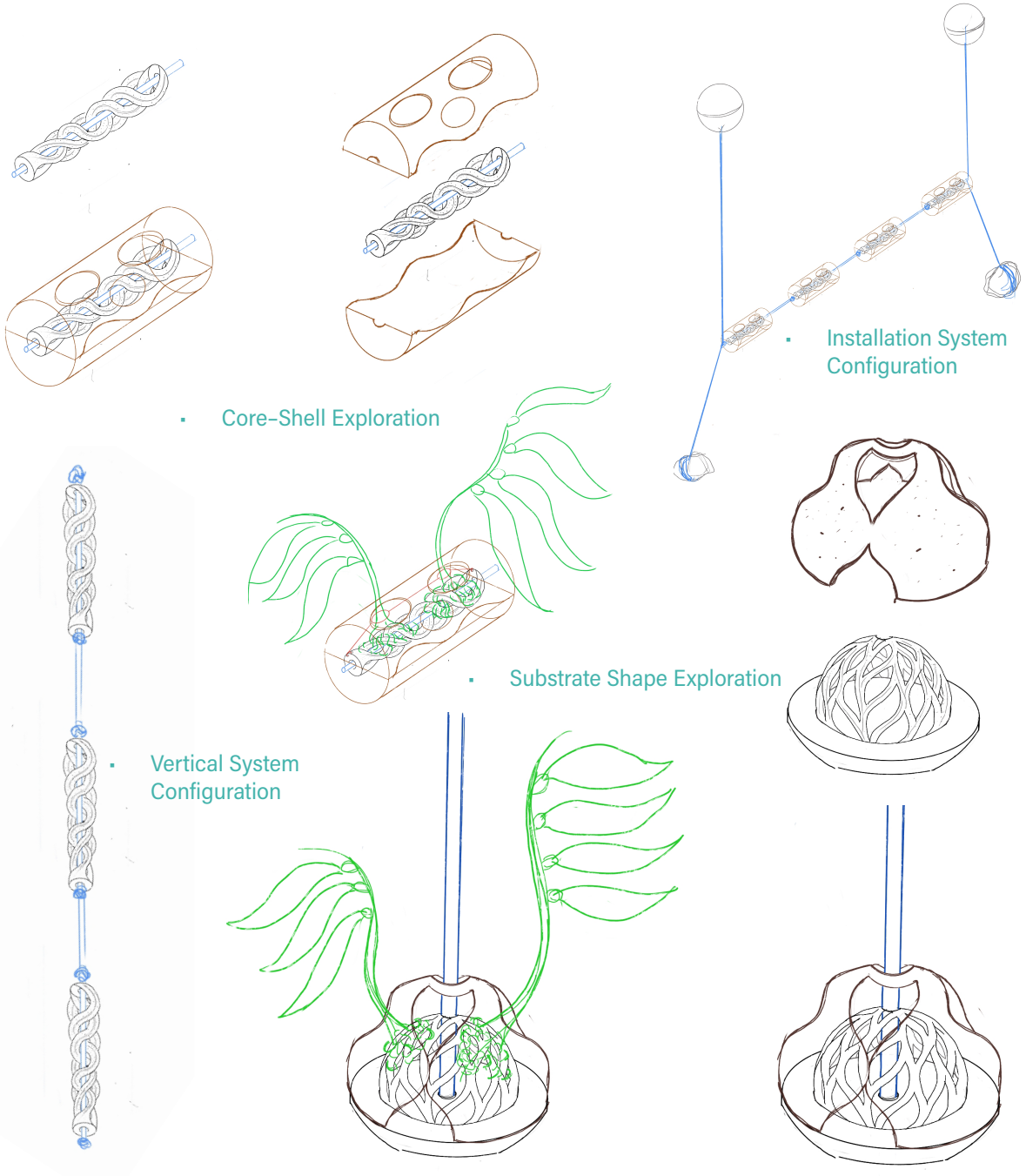
- Material and Fabrication Logic

7. Temporal Ecological Coherence
Material selection must ensure structural reliability during the active phase of intervention while minimizing residual environmental impact beyond its functional lifespan.

8. Contextual Fabrication Accessibility
The system must be manufacturable using locally accessible materials and low-complexity fabrication processes, ensuring compatibility with small-scale, community-based restoration contexts.

6.3 First Concept Explorations

Iterative structural hypotheses exploring **system configuration, protection–release mechanisms and anchorage geometry.**



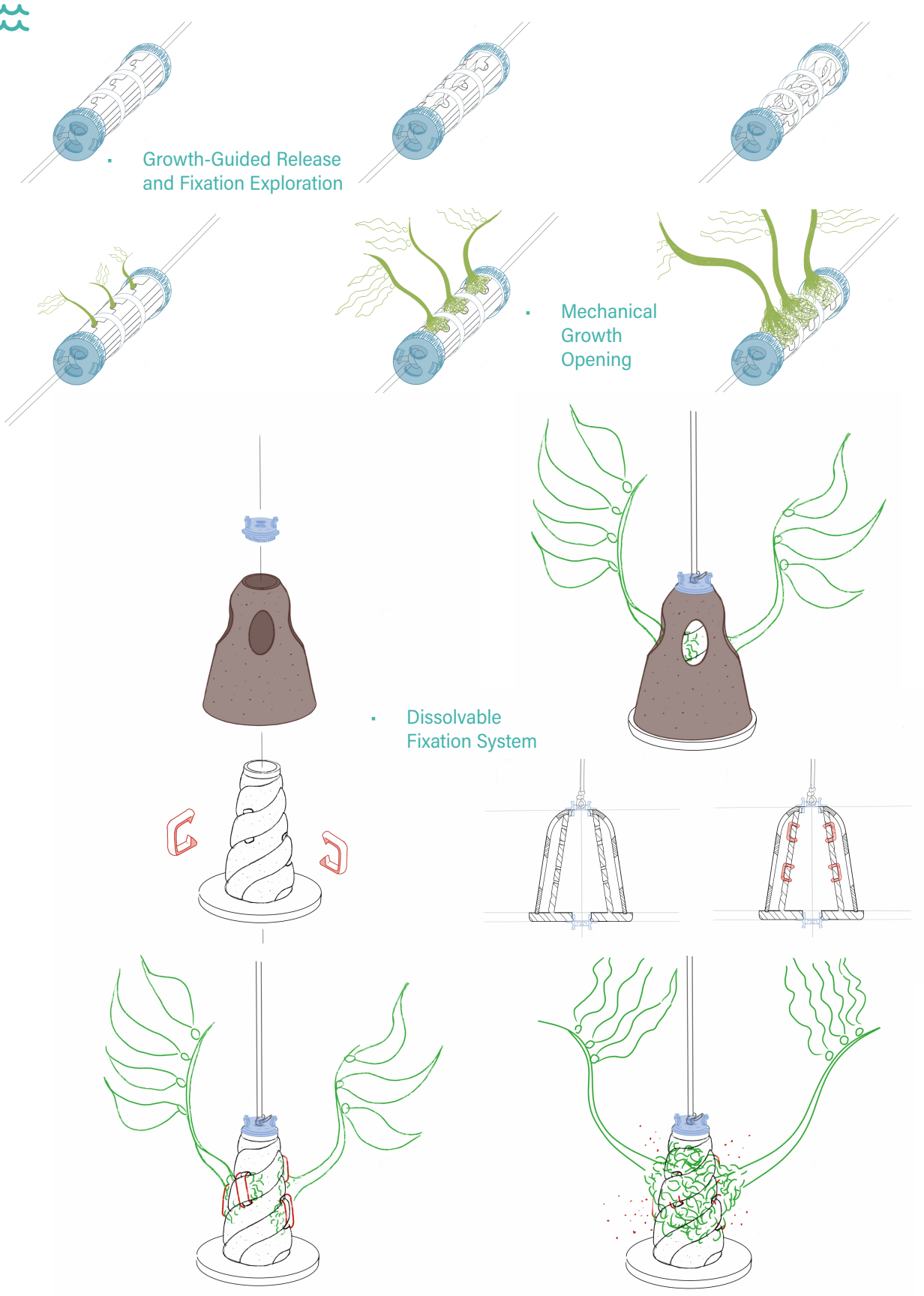


Figure 24: Iterative concept explorations of the modular kelp restoration system, examining core–shell configurations, anchorage geometries, and growth-responsive fixation mechanisms (author's own elaboration).

6.4 The Controlled Fracturable Capsule as Design Strategy

Structural mediator between juvenile stabilization and autonomous attachment.

This strategy provides initial protection, guided fixation, and buoyancy balance during early establishment. Designed to **fracture progressively under biological growth** and environmental exposure, the capsule releases mechanical constraint as the holdfast expands, transitioning from assisted support to passive substrate.

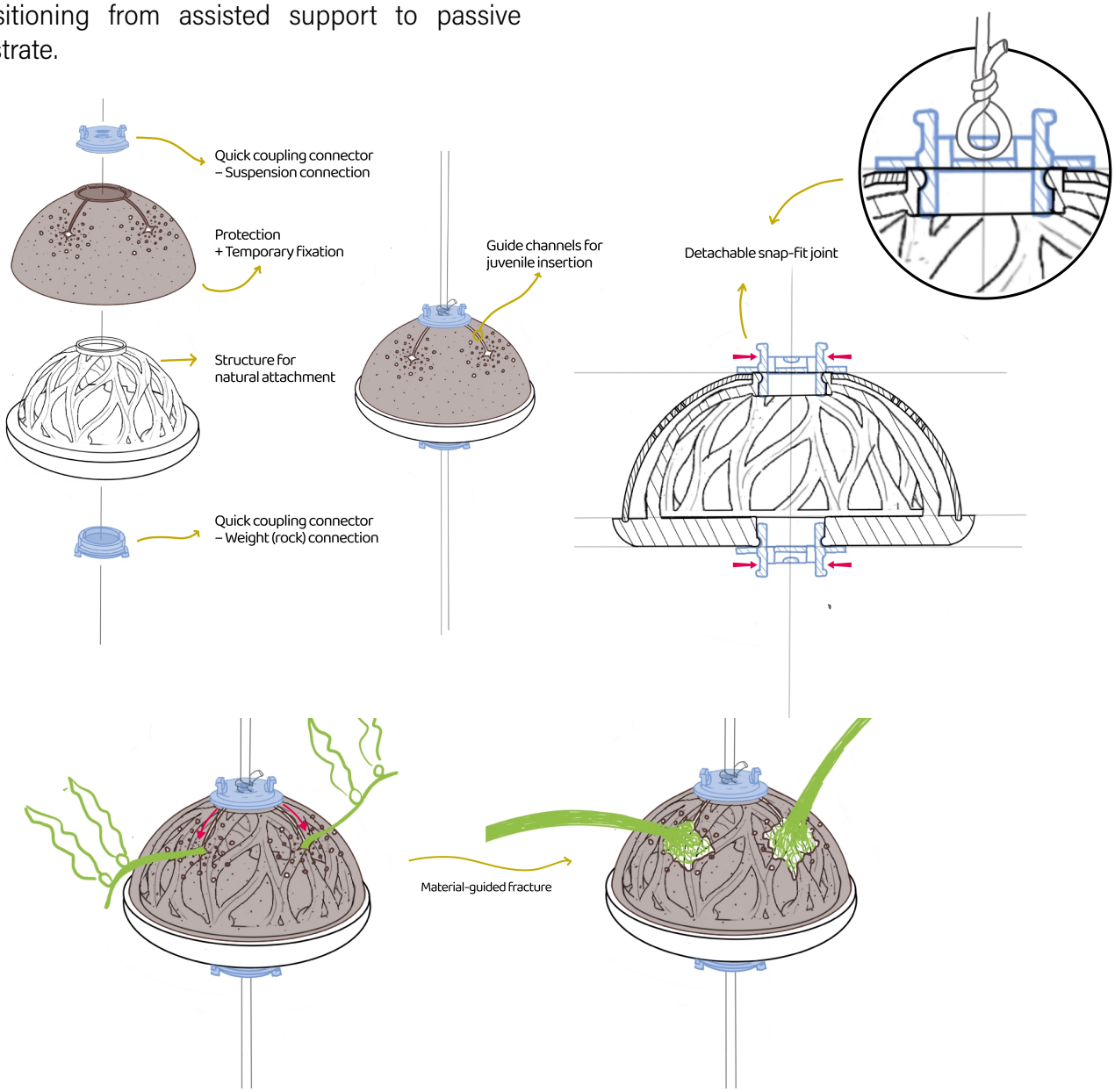


Figure 25: Conceptual diagram of the controlled fracturable capsule illustrating its role as a temporary structural mediator between juvenile stabilization and autonomous attachment (author's own elaboration).

Iterative Formal Evolution

Components and geometry definition.

While the structural principle of controlled fracture and temporary stabilization remained constant, the formal configuration evolved through iterative refinement.

In this case the form follows the vertical axis of the suspension rope while enabling a **more balanced mass distribution** along the system.
Surface articulations were progressively calibrated to improve manufacturability.
Component interfaces were then refined to **simplify manual installation.**

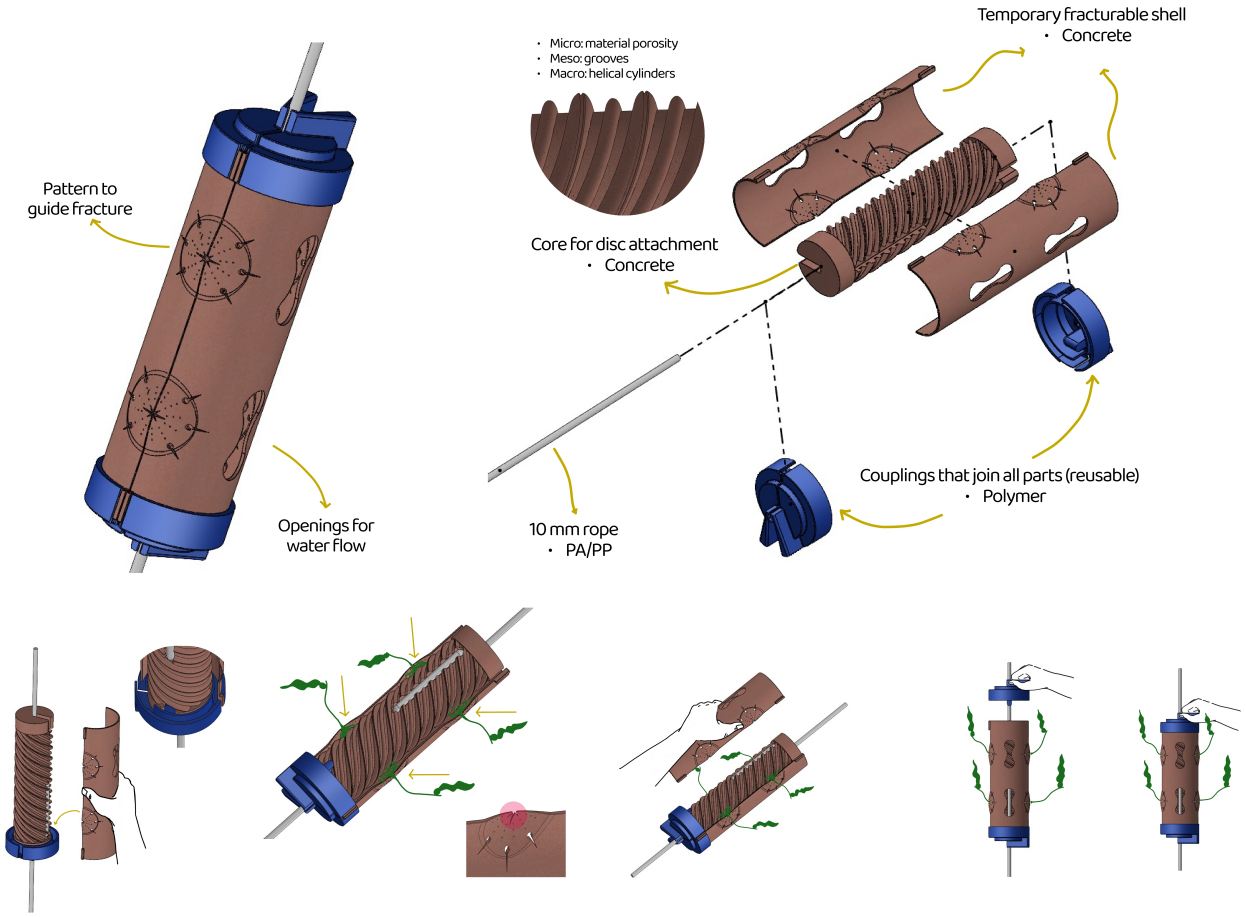


Figure 26: Iterative formal evolution of the suspended system, showing refinement to improve manufacturability and manual installation. (author's own elaboration).

6.4 The Controlled Fracturable Capsule as Design Strategy

Iterative Formal Evolution

Components and material simplification

This iteration focused on **material homogenization and component simplification.** The geometry was refined to respond more directly to the algae structure, improving growth accommodation.

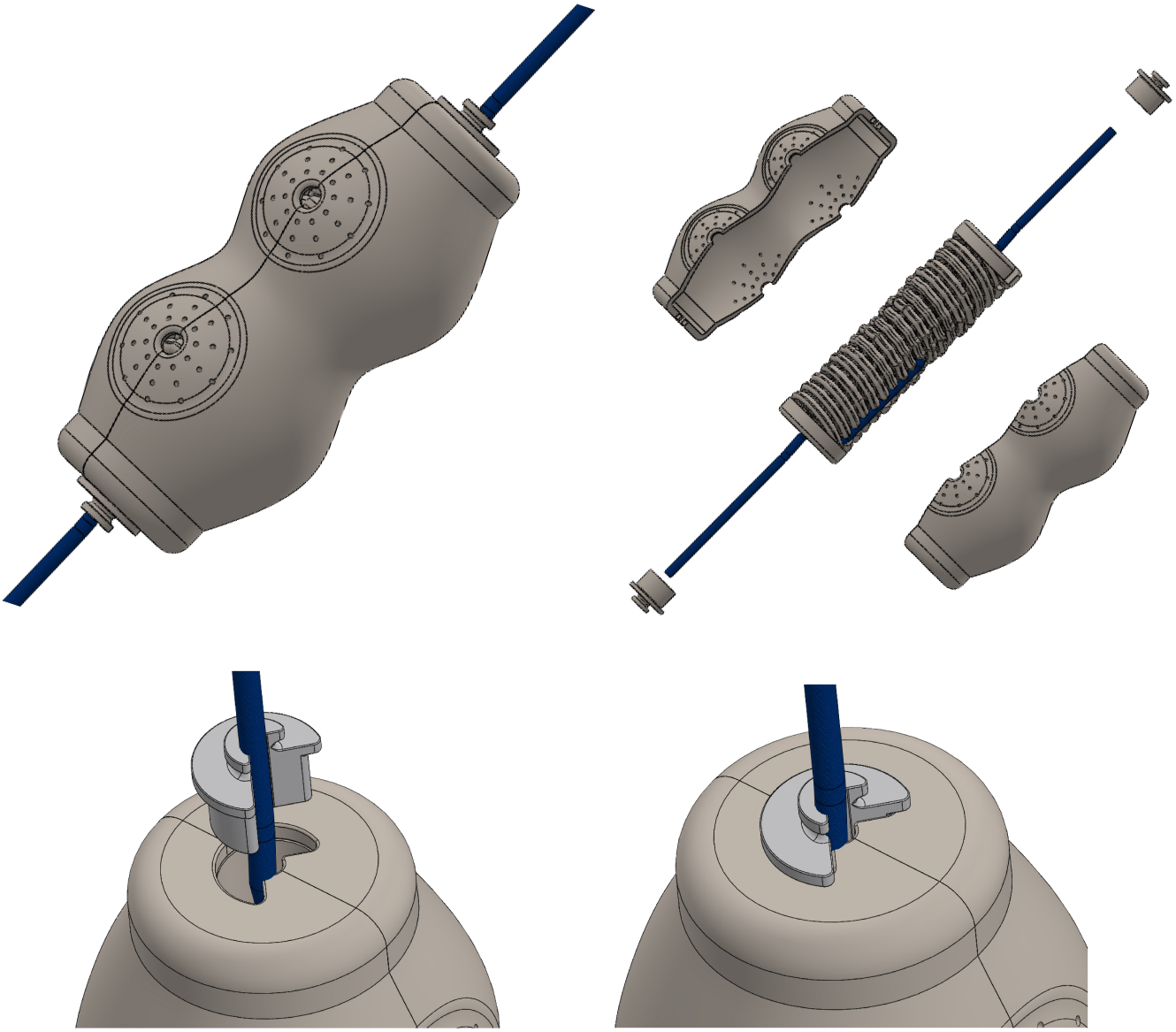


Figure 27: Further iteration focused on material homogenization and component simplification (author's own elaboration).



6.5 Designing Under Biological Uncertainty

As the concept advanced from structural definition toward material specification, it became increasingly clear that certain components (particularly the outer shell) would require multiple prototyping iterations. Its intermediate geometric complexity, controlled fracture logic, and interaction with living tissue could not be fully anticipated through modelling alone. Material clarification did not reduce uncertainty; it made it more visible.

During this phase, fundamental questions emerged in dialogue with the collaborating marine biologist: ***How will the algae respond to the structure? Will the algae actually push against the structure as anticipated?*** The capsule was designed with the expectation that holdfast expansion would exert pressure to fracture the shell. Yet innovative experimentation in kelp restoration remains limited, and there is comparatively little documented knowledge about how juvenile *Macrocystis pyrifera* interacts with newly introduced infrastructures. **The biological response could not be assumed.**

At that moment, the design shifted from a solution toward a hypothesis; one whose validity could only be determined through testing.

From a *more-than-human* design perspective, treating a living system as something expected to behave according to a predefined mechanical outcome risks reinforcing human-centered control assumptions. **Living organisms are not passive materials**; they grow, adapt, and respond in their own ways. Designing under biological uncertainty therefore cannot rely on imposing a rigid solution and simply testing awaiting validation.

Instead, **uncertainty must be reframed as a condition for learning**. The role of design becomes the creation of enabling structures that allow the biological agent to **express its behavior**, making that behavior **observable and informative**. In this sense, the capsule is reconceived not as a finalized object but as an **experimental mediator**; a device through which interaction, resistance, adaptation, and growth can reveal new parameters for subsequent design decisions.

This shift in perspective required a reconsideration of the initial configuration. Rather than refining a fixed structural proposal to better enforce its intended behavior, the system was redesigned to accommodate uncertainty more explicitly, allowing biological response to inform structural adaptation.

The redesign presented in the following section emerges from this reframing. It represents not a correction of error, but a **translation of biological uncertainty into design evolution.**

from validating a hypothesis



to designing conditions for learning

6.6 Experimental Design Configurations

To translate biological uncertainty into testable design knowledge, the redesigned system was structured as a **set of four experimental module configurations (C1–C4)**. Rather than assuming how the holdfast will behave, these configurations define **controlled conditions to observe** whether juvenile Macrocystis pyrifera tends to push against an intended fracture zone or instead redirects growth toward alternative pathways.

Two variables were defined:

- **Level of confinement**

Defined as the degree to which the internal geometry restricts holdfast expansion before mechanical contact with the inner shell occurs. This variable regulates the timing, intensity, and distribution of growth-induced pressure against the capsule wall. By modulating the available expansion volume, the system allows observation of whether the holdfast adapts its morphology under spatial constraint, concentrates force toward a fracture zone, or redirects growth when resistance is encountered.

- **Presence or absence of alternative exit pathways**

Refers to whether lateral openings are incorporated into the shell geometry, providing potential redirection routes for holdfast expansion. This variable tests whether growth-driven mechanical force is primarily pressure-seeking (concentrated against the frontal constraint following the natural growth path) or opportunity-seeking (redirected toward available openings). By introducing or removing alternative pathways, the configuration allows observation of how the holdfast negotiates resistance: whether it accumulates stress to activate fracture zones or adapts its morphology to exploit accessible spatial gradients.

Together, these variables generate a simple comparative matrix: high vs. low confinement and closed vs. open pathways, through which kelp–structure interaction can be observed under distinct, designed conditions:

C1 – High confinement, no alternative exits
Configuration with minimal internal volume and no alternative exit pathways. The holdfast remains fully contained within the structure.

C2 – High confinement, with alternative exits
Configuration with minimal internal volume and alternative exit pathways. The holdfast has limited space for growth and the possibility of interacting with the external environment.

C3 – Low confinement, no alternative exits
Configuration with increased internal volume and no alternative exit pathways. The holdfast remains fully contained within the structure but with greater space for growth.

C4 – Low confinement, with alternative exits
Configuration with increased internal volume and alternative exit pathways. The holdfast has greater space for growth and the possibility of interacting with the external environment.

C1

High confinement
No alternative exits

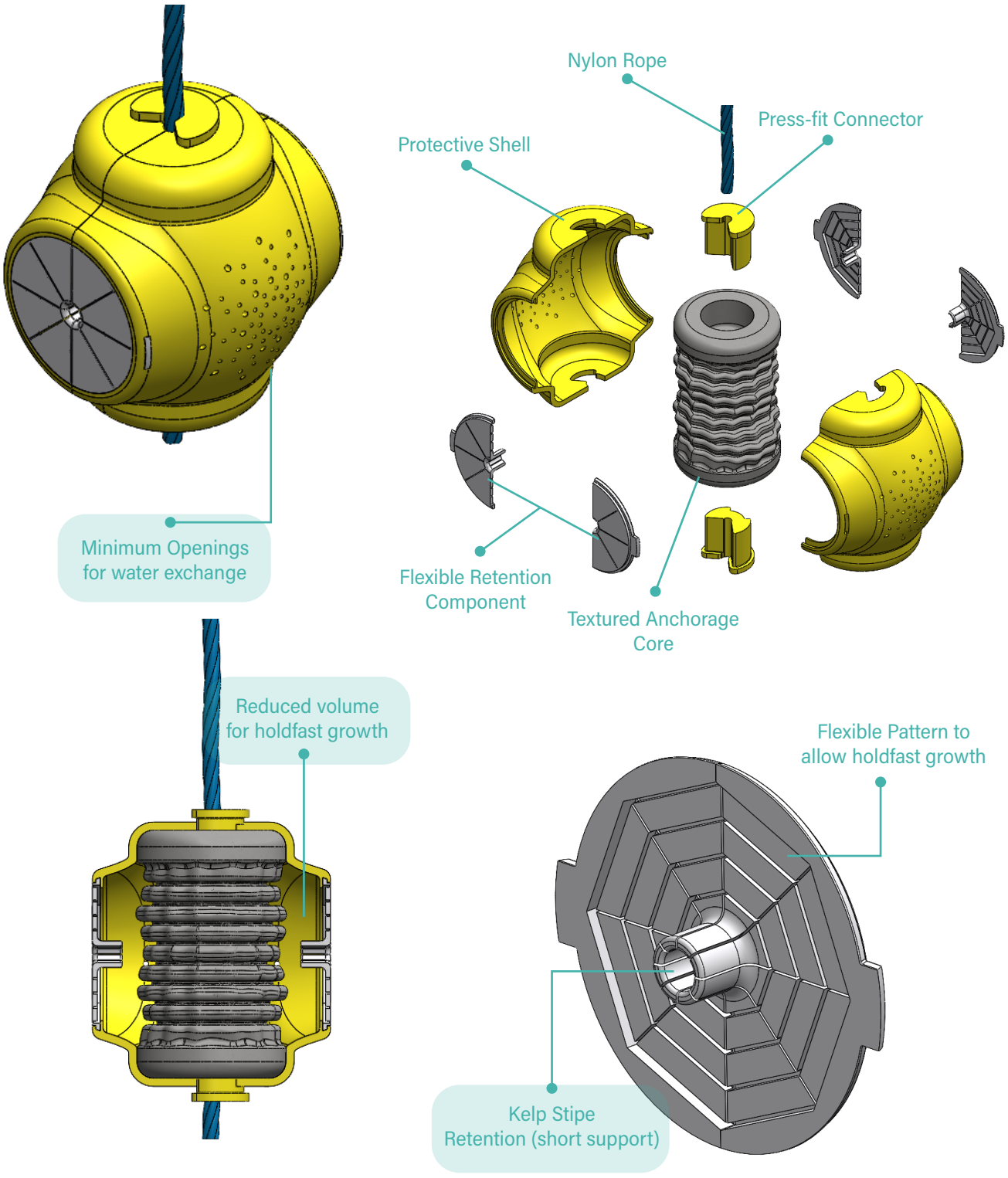


Figure 28: C1 configuration. High internal confinement without alternative growth exits, limiting lateral expansion while prioritizing controlled early stabilization (author's own elaboration).

C2

High confinement
Alternative exits

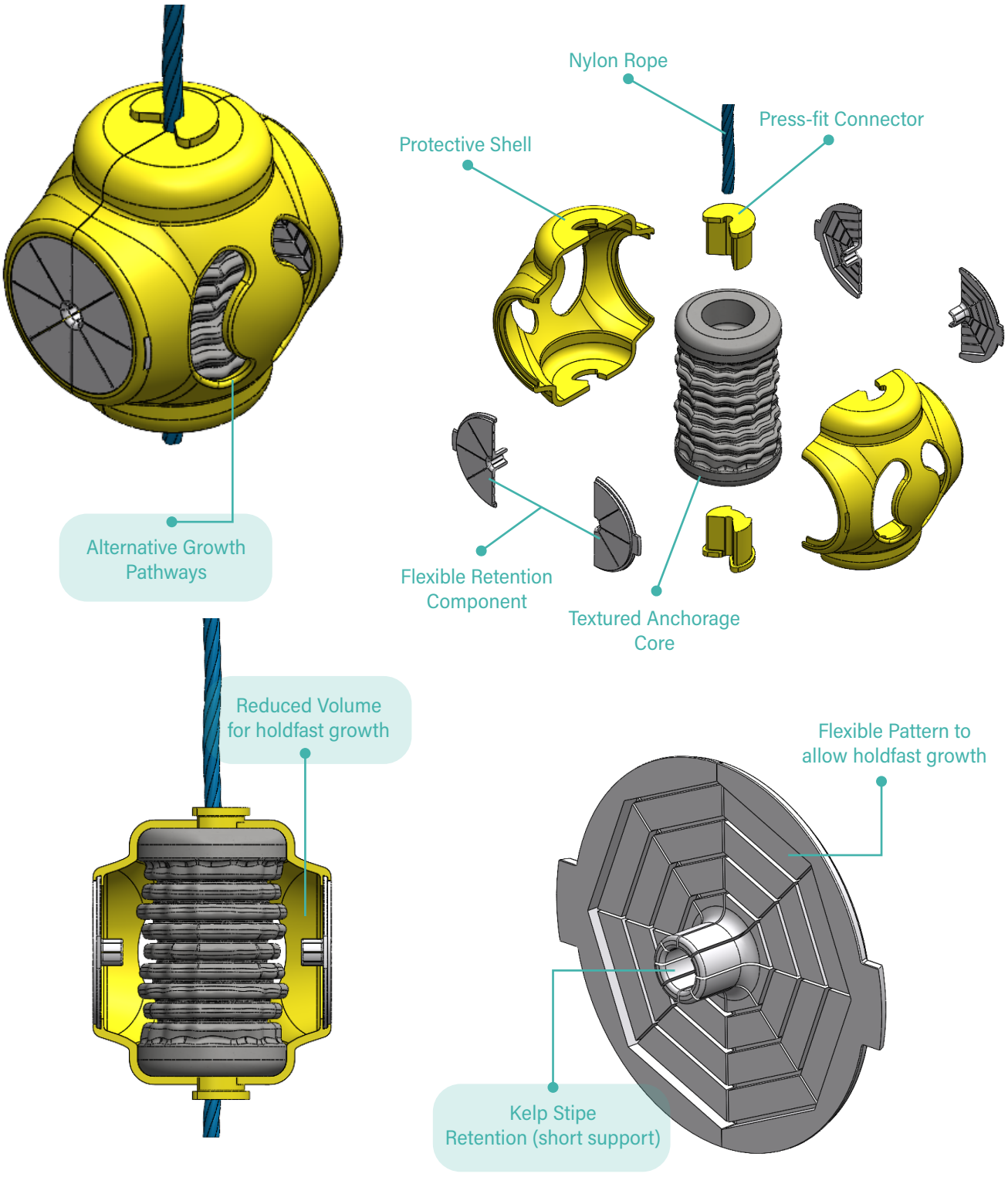


Figure 29: C2 configuration. High internal confinement with lateral openings, enabling alternative growth pathways under restricted volume conditions (author's own elaboration).

C3

Low confinement
No alternative exits

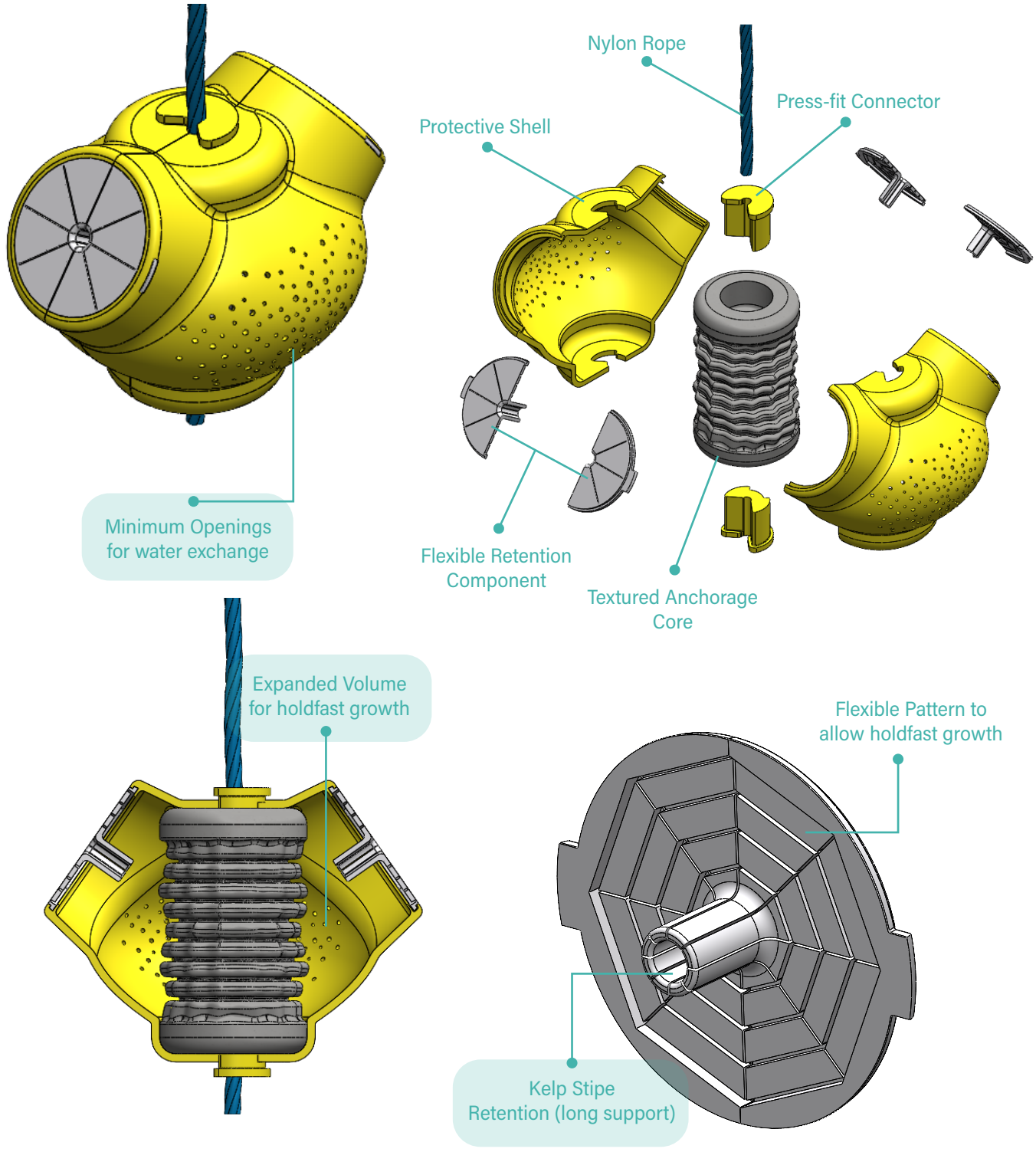


Figure 30: C3 configuration. Reduced confinement without alternative exits, allowing expanded holdfast growth within a single primary pathway (author's own elaboration).

C4

Low confinement
Alternative exits

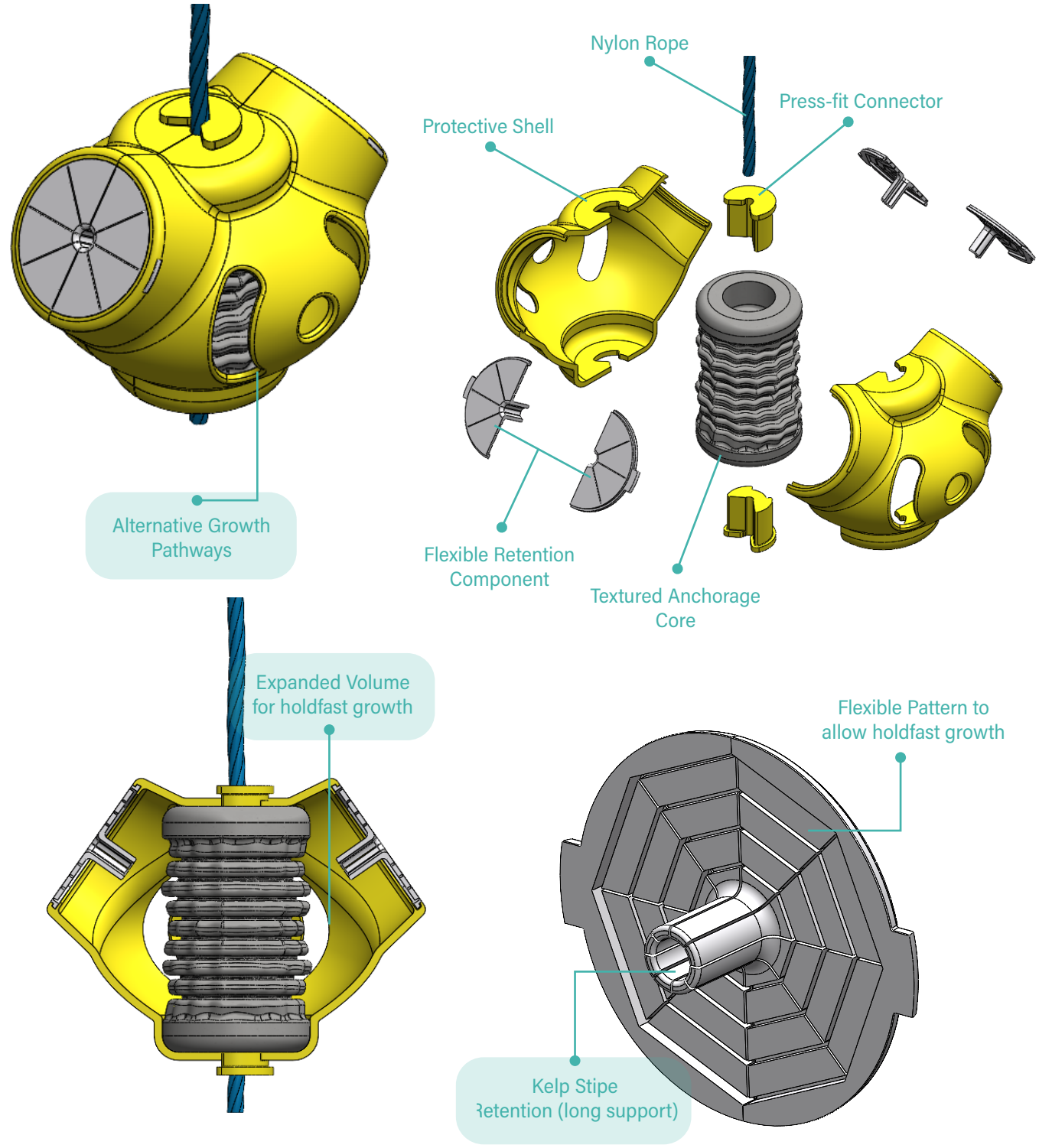


Figure 31: C4 configuration. Reduced confinement with lateral openings, combining expanded internal volume and multiple potential growth trajectories (author's own elaboration).

7. Material Selection Research

This chapter examines the material strategies underpinning the system's structural logic. Through constraint-based screening and objective-driven ranking, candidate materials are evaluated according to marine environmental compatibility, mechanical behavior, fabrication accessibility, and cost. The analysis translates ecological and operational requirements into component-specific material decisions, ensuring coherence between biological function, structural performance, and prototyping feasibility.

7.1 Textured Anchorage Core

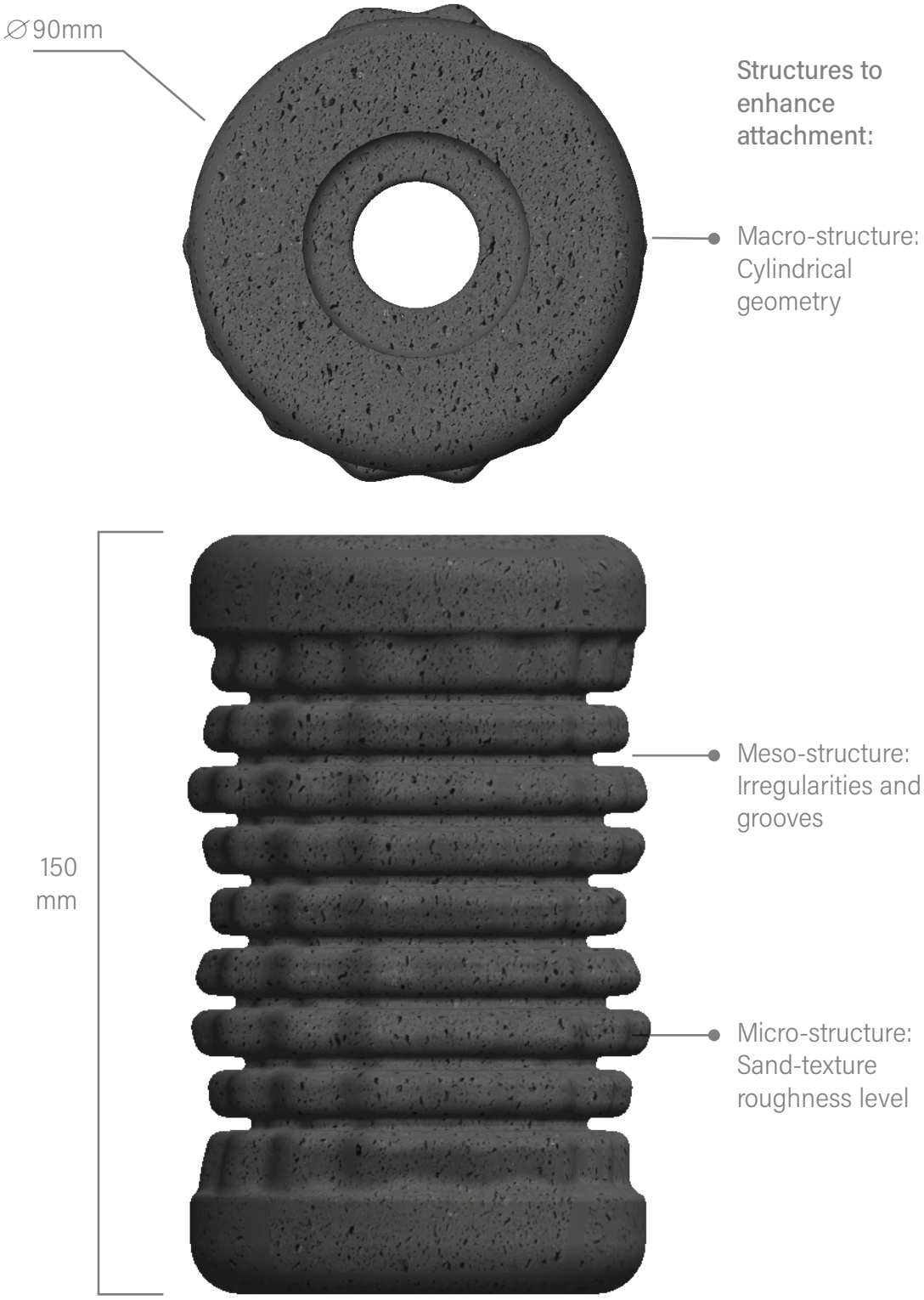


Figure 32: Textured Anchorage Core.Cylindrical core integrating multi-scale surface textures to promote holdfast attachment (author's own elaboration).

Precedent Analysis of Innovative Marine Restoration Systems

The references analyzed in this section correspond to the same projects discussed in Chapter 2.6, Overview of Worldwide Emerging and Innovative Approaches. These initiatives were selected because they represent state-of-the-art efforts in ecological engineering and marine restoration, particularly in contexts where conventional conservation strategies are insufficient.

Screening by Constraints

- Marine environmental compatibility
- Manufacturing compatibility
- Structural stability in seawater

Ranking by Objectives

- Biological performance
- Availability / Cost-efficiency

Table 4.
Selected international artificial reef restoration systems.

Nº (2.6)	Referent	Function	Material
1	Ørsted Reef Design Lab	Large-scale artificial reef units for restoration and biodiversity enhancement in coastal environments.	**70 % arena + 30 % pozzolanic cement.**
2	Archireef	Coral restoration system composed of interlocking hexagonal tiles optimized for coral growth and adhesion.	**Terracotta**
3	MARS Reef Design Lab	Modular ceramic reef system designed to promote coral colonization and marine biodiversity through bioinspired geometry.	**Marine-grade cementitious mix (limestone + sand + Portland cement binder).**
4	Reef Ball Foundation	Modular artificial reef units designed for habitat restoration and coastal protection.	**Reinforced concrete (cement + sand + microsilica) poured into fiberglass molds.**
5	rrreefs	Modular ceramic reef system fostering coral, algae, and invertebrate colonization through porous 3D structures.	**Terracotta**
6	Living Seawalls Reef Design Lab	Eco-engineered seawall panels enhancing marine life settlement on coastal infrastructures.	**Marine-grade concrete (Portland cement + sand + crushed shell + limestone aggregate).**
7	EMU Reef Design Lab	Small modular reef units combining bioactivity with lightweight construction for flexible deployment.	**Bioactive concrete (cementitious mix with limestone, sand, and crushed shells).**

7.1 Textured Anchorage Core

Table 5.
Overview of artificial reef restoration projects grouped by material category.

Category	Projects	Material
Cementitious / Marine Concrete	Ørsted, MARS, ReefBall, Living Sea Walls, EMU	**Portland Cement + sand mixed with:** ▪ **Pozzolanics** ▪ **Microsilica** ▪ **Limestone** ▪ **Shells**
Ceramic / Terracotta	ArchiReef, Rrreefs	**Natural clay, fired (1000 °C).**

Pozzolans: Siliceous or aluminous materials (generally ash-based) that react with calcium hydroxide in cement, improving durability and reducing alkalinity.

Microsilica: An ultrafine silica powder (an industrial by-product) that increases the density and mechanical strength of concrete.

Limestone: Ground limestone rich in calcium carbonate ($CaCO_3$) that helps reduce alkalinity and enhances biological compatibility.

Constraints

Parameters

Marine environmental compatibility:
pH stability and absence of toxic ion leaching when exposed to seawater (synthetic or natural).

- Maximum variation of seawater pH ($\Delta pH \leq \pm 1.0$) , relative to natural seawater baseline ($\approx 8.1–8.2$).
- Metal ion leaching (Negligible, very low, low, high)

Manufacturing compatibility
Can be processed with accessible fabrication technologies and without specialized industrial infrastructure.

- Compatible with low-cost fabrication (yes/no)
- Compatible with accesible processing infraestructure (yes/no)

Structural stability in seawater
Resistance to dissolution, swelling, or mechanical degradation during long-term marine exposure.

- Water absorption % (≤ 5 % resistant, > 10 % high degradability)
- Compressive strength MPa (≥ 40 MPa strong, < 20 MPa weak).

Table 6.
Constraint-based evaluation of candidate materials for the Textured Anchorage Core.

Material	Marine environmental compatibility	Manufacturing compatibility	Structural stability in seawater Water absorption / Compressive strenght	Evaluation
Portland + Pozzolans	pH ≈ 8–9 Low metal ion leaching	Low-cost fabrication: yes Accessible processing infrastructure: yes	≤ 5–8 % (resistant) / 40–60 MPa (strong)	**Pass**
Portland + Microsilica	pH ≈ 8–9 Very low metal ion leaching	Low-cost fabrication: yes Accessible processing infrastructure: yes	≤ 5 % (resistant)/ > 60 MPa (high strength)	**Conditional Pass**
Portland + Limestone	pH ≈ 8–9 Low metal ion leaching	Low-cost fabrication: yes Accessible processing infrastructure: yes	~5–8 % (resistant) 40–55 MPa (strong)	**Pass**
Portland + Shells	buffers pH in short terms Low metal ion leaching	Low-cost fabrication: yes Accessible processing infrastructure: yes	Variable % depending on shell content 40–50 MPa (strong)	**Conditional Pass**
Natural clay (Terracotta)	pH neutral Negligible metal ion leaching	Low-cost fabrication: yes Accessible processing infrastructure: no o (kiln required)	5–10 % (risk of long-term degradation) 20–40 MPa (moderate strength)	**Fail**

Comments

Portland-based mixes incorporating pozzolans or limestone present the most balanced performance in terms of environmental compatibility, manufacturing feasibility, and structural stability.
However, the use of microsilica could be considered exclusively for the core, depending on the need to enhance mechanical strength or resistance to prolonged seawater exposure.

The use of shells, although less effective in buffering pH, may provide additional benefits related to biocompatibility.

Therefore, a ranking based on the defined objectives becomes necessary.

7.1 Textured Anchorage Core

Objectives	Parameters
Biological performance Capacity of the material to promote marine life colonization by offering chemical and physical conditions favorable for attachment and growth of marine organisms.	▪ Presence of $CaCO_3$ or Ca^2 contributing to chemical stability and bio-mineralization. ▪ Enables micro-scale irregularities supporting attachment and biofilm formation.
Availability Degree to which the material is available locally.	▪ Locally sourced, suppliers availability.
Cost Degree to which the material is affordable.	▪ Cost chilean peso $/kg

Table 7.
Objectives-based ranking of candidate materials for the Textured Anchorage Core.

Material	Biological Performance	Availability	Cost (Portland base: $160–200 CLP/kg)	Ranking
Portland + Pozzolans	★★ No direct $CaCO_3$ source Microtopography achievable	★★ Volcanic sources in Chile, limited commercial standardization	?	2º
Portland + Microsilica	★ No carbonate contribution Limits micro-porosity	★ Imported material (Europe/Asia suppliers)	★ High (~850–1140 CLP/kg)	3º
Portland + Limestone	★★★ $CaCO_3$ presence Favorable surface complexity	★★★ Abundant local limestone deposits	★★★ Low (~45–140 CLP/kg)	1º
Portland + Shells	★★ Biogenic $CaCO_3$ Variable surface characteristics	★★ Local recycled shells, not standardized	?	2º

Results

Among the evaluated combinations, Portland + Limestone presents the best balance between biological performance, availability, and cost, standing out for its $CaCO_3$ content and adequate pH stability for marine applications.

Mixes incorporating pozzolans or shells show local potential and sustainability advantages; however, they still lack standardized composition or established commercial control.

In contrast, Portland + Microsilica, although it enhances mechanical strength, appears less biocompatible and more costly within the context of marine restoration.

Therefore, Portland cement combined with limestone is selected for core fabrication using mold-based casting processes.

The screening and ranking criteria for the anchorage core were established based on concrete durability literature and eco-engineered coastal infrastructure research. Performance thresholds for water absorption, compressive strength, and chemical stability in seawater were derived from concrete technology references (Neville, 2011; Mehta & Monteiro, 2014; Thomas, 2013). Considerations regarding $CaCO_3$ content and ecological compatibility were informed by marine eco-engineering studies (Firth et al., 2014; Strain et al., 2018; Perkol-Finkel & Sella, 2015).

7.2 Protective Shell & Press-fit Connector

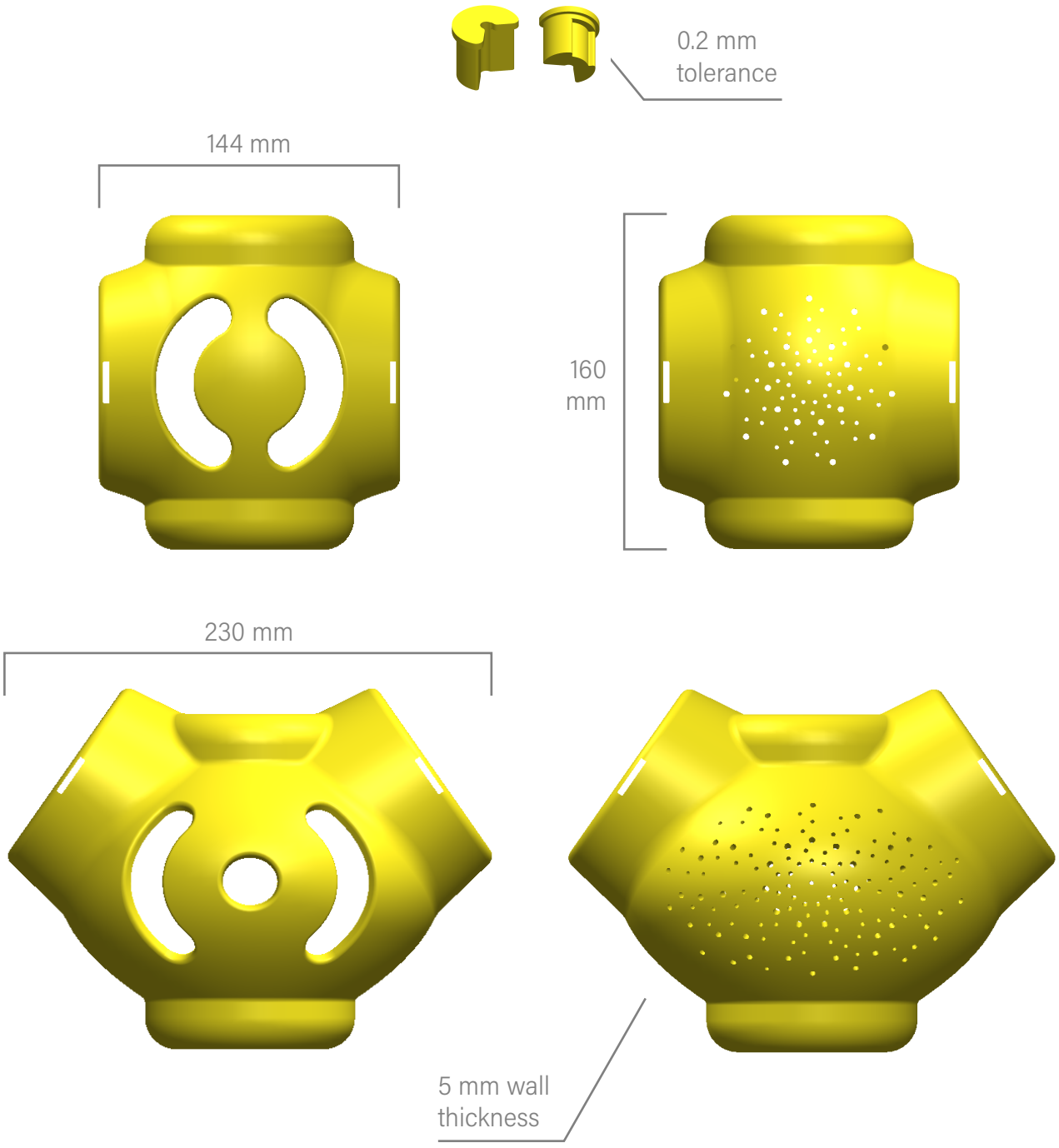


Figure 33: Protective Shell and Press-fit Connector. Protective shell with perforated surface and press-fit tolerance, designed for modular assembly and core integration (author's own elaboration).

Material Candidates Compatible with Additive Manufacturing

The protective shell and press-fit connector are conceived as iterative learning prototypes rather than permanent industrial components. Therefore, material selection prioritizes compatibility with accessible additive manufacturing processes (FDM), enabling rapid fabrication, testing.

Materials requiring industrial-scale production methods were excluded, as they would limit iterative development, increase cost and fabrication time, and contradict the exploratory nature of this research phase.

Table 8.
Material candidates compatible with FDM manufacturing for the Protective Shell and Press-fit Connector.

Material	Description
PLA	Biobased thermoplastic polymer (polylactic acid)
PETG	Glycol-modified polyethylene terephthalate thermoplastic
ABS	Acrylonitrile butadiene styrene thermoplastic; impact-resistant
ASA	Acrylonitrile styrene acrylate thermoplastic; UV-stable
Nylon (PA)	Polyamide engineering thermoplastic

Screening by Constraints

- Marine environmental compatibility
- Mechanical stability

Ranking by Objectives

- Print performance
- Availability / Cost-efficiency

7.2 Protective Shell & Press-fit Connector

Constraints	Parameters
Marine environmental compatibility Resistance to degradation when exposed to seawater conditions, without significant short-term pollutant release (3 months).	▪ Water absorption level (low / medium / high) ▪ Dimensional stability after marine exposure (stable / minor change / unstable) ▪ Surface degradation under UV-salt exposure (none / moderate / severe) ▪ Pollutant release (yes/no)
Mechanical stability Ability to maintain structural integrity and dimensional accuracy under mechanical loading and marine exposure.	▪ Retention of mechanical strength after 3 months seawater exposure (intact / minor reduction / severe degradation) ▪ Press-fit dimensional stability under wet conditions (no loosening / minor tolerance shift / loss of interference)

Table 9.
Constraint-based evaluation of candidate materials for the Protective Shell and Press-fit Connector.

Material	Marine environmental compatibility	Mechanical stability	Evaluation
PLA	Water absorption: medium; Dimensional stability: minor change; UV-salt degradation: moderate–severe; Pollutant release (3 months): no	Mechanical strength retention: minor reduction to severe degradation; Press-fit stability: risk of loosening over time	**Fail**
PETG	Water absorption: low; Dimensional stability: stable; UV-salt degradation: moderate; Pollutant release (3 months): no	Mechanical strength retention: intact to minor reduction; Press-fit stability: no loosening	**Pass**
ABS	Water absorption: medium; Dimensional stability: minor change; UV-salt degradation: severe (UV-sensitive); Pollutant release (3 months): no	Mechanical strength retention: intact; Press-fit stability: minor tolerance shift possible	**Conditional Pass**
ASA	Water absorption: low; Dimensional stability: stable; UV-salt degradation: none to minor; Pollutant release (3 months): no	Mechanical strength retention: intact; Press-fit stability: no loosening	**Pass**
Nylon (PA)	Water absorption: high; Dimensional stability: unstable (swelling); UV-salt degradation: minor; Pollutant release (3 months): no	Mechanical strength retention: minor reduction; Press-fit stability: loss of interference likely	**Conditional Pass**

Comments

PETG and ASA present the most balanced performance for short-term marine exposure (≈ three months), combining low water absorption, adequate resistance to environmental degradation, and sufficient rigidity to maintain press-fit dimensional accuracy.

ABS remains a viable option under controlled conditions, though its UV sensitivity may affect stability in prolonged outdoor exposure.

PLA appears less suitable due to hydrolytic degradation and reduced mechanical reliability in wet environments. Nylon (PA), while mechanically strong, exhibits significant moisture absorption that may compromise dimensional stability.

Therefore, a ranking based on the defined objectives becomes necessary to support final material selection.

7.2 Protective Shell & Press-fit Connector

Objectives	Parameters
Print performance Ability of the material to enable reliable, precise, and repeatable fabrication using accessible FDM 3D printing.	▪ Good layer adhesion and low warping tendency. ▪ Dimensional accuracy suitable for press-fit tolerances. ▪ Stable printing without requiring specialized equipment.
Availability / Cost-efficiency Degree to which the material is accessible and economically viable for rapid prototyping.	▪ Commercial availability in local or regional suppliers. ▪ Affordable cost per kilogram.

Table 10.
Objectives-based ranking of candidate materials for the Protective Shell and Press-fit Connector.

Material	Print performance	Availability / Cost-efficiency	Ranking
PETG	★★★ Reliable printing in closed printers; low warping; good dimensional accuracy for press-fit.	★★★ Widely available; affordable; no special storage required.	1º
ABS	★★ Good printability in closed printers; high warping; requires controlled temperature; stable geometry.	★★ Available but typically higher cost than PETG.	2º
ASA	★★ Good printability in closed printers; medium warping; requires controlled temperature; stable geometry.	★★ Available but typically higher cost than PETG.	2º
Nylon (PA)	★ More complex printing; moisture-sensitive; dimensional variability.	★ Higher cost; requires dry storage and handling.	3º

Results

Among the evaluated thermoplastics, PETG presents the most balanced performance in terms of print reliability, dimensional accuracy, and availability, making it particularly suitable for iterative prototyping through accessible FDM fabrication.

ASA and ABS remain viable alternatives, especially in scenarios requiring enhanced UV resistance or mechanical robustness; however, they involve greater printing complexity and cost considerations. Nylon (PA), although mechanically strong, introduces dimensional instability due to moisture absorption, which may compromise press-fit tolerances in marine environments.

Therefore, PETG is selected for the fabrication of the protective shell and press-fit connector using FDM-based rapid prototyping processes.

The screening and ranking of thermoplastic materials for the protective shell and press-fit connector was based on polymer engineering and marine degradation literature. Criteria related to moisture absorption, dimensional stability, and UV–salt exposure were derived from established materials science references (Callister & Rethwisch, 2018; Osswald & Menges, 2012; Gewert et al., 2015; ASTM D570). FDM mechanical performance and interlayer behavior were informed by additive manufacturing studies (Tymrak et al., 2014; Torrado & Roberson, 2016).

7.3 Flexible Retention Component

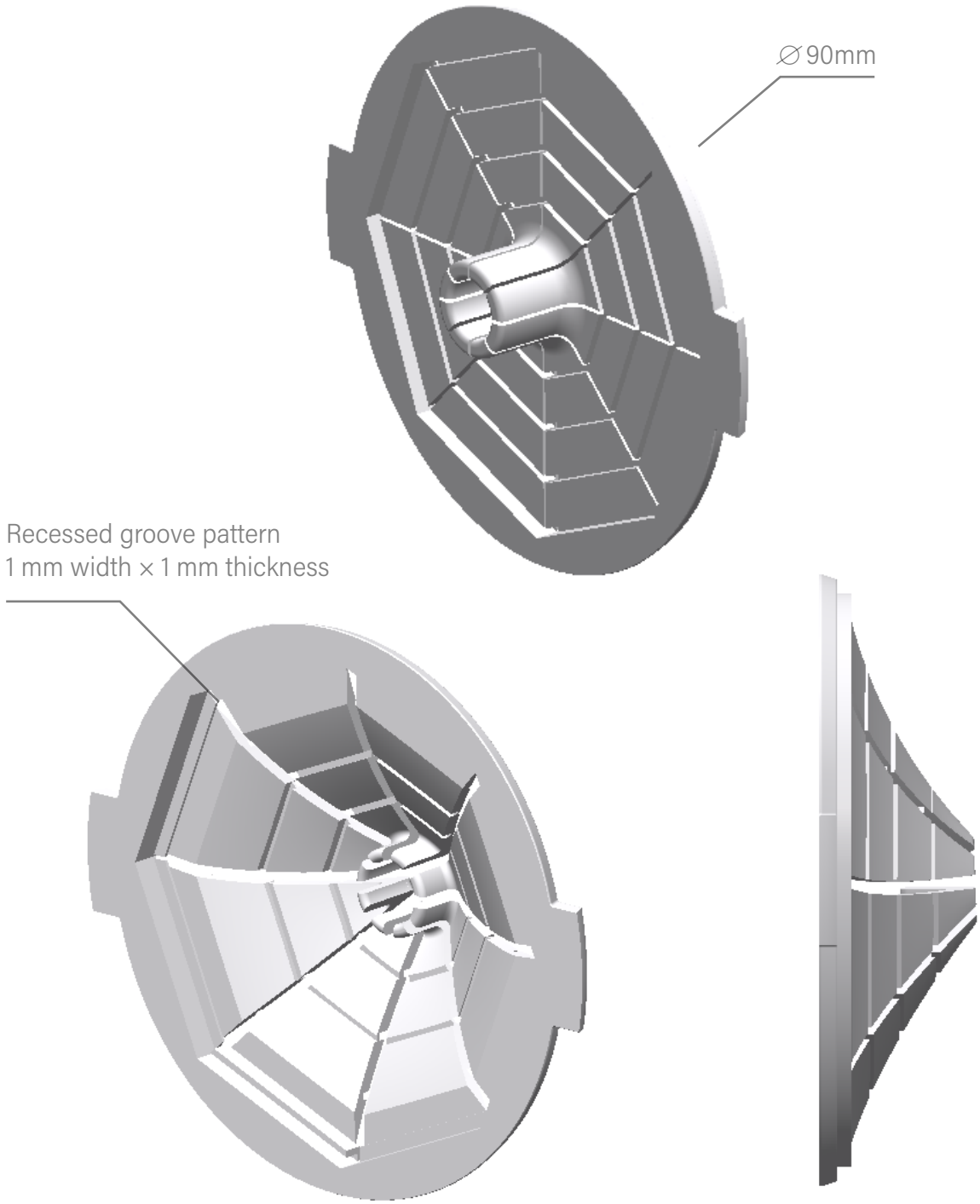


Figure 34: Flexible Retention Component. Flexible element with recessed groove pattern enabling controlled bending under growth-driven expansion (author's own elaboration).

Material Candidates Compatible with Additive Manufacturing

The Flexible Retention Component is conceived as an iterative learning prototype rather than a permanent industrial component. Therefore, material selection prioritizes compatibility with accessible additive manufacturing processes (FDM), enabling rapid fabrication and testing.

Additionally, selected materials must allow controlled flexural behavior, whether through intrinsic material ductility or geometry-driven flexibility.

Screening by Constraints

- Marine environmental compatibility
- Mechanical stability

Ranking by Objectives

- Low elastic modulus in bending
- Availability / Cost-efficiency

Table 11.
Material candidates compatible with FDM manufacturing and flexural behavior for the Flexible Retention Component.

Material	Description
TPU	Thermoplastic polyurethane elastomer; highly flexible and abrasion-resistant
PETG	Glycol-modified polyethylene terephthalate thermoplastic
ABS	Acrylonitrile butadiene styrene thermoplastic; impact-resistant
ASA	Acrylonitrile styrene acrylate thermoplastic; UV-stable
Nylon (PA)	Polyamide engineering thermoplastic

7.3 Flexible Retention Component

Constraints	Parameters
Marine environmental compatibility Resistance to degradation when exposed to seawater conditions, without significant short-term pollutant release (3 months).	▪ Water absorption level (low / medium / high) ▪ Dimensional stability after marine exposure (stable / minor change / unstable) ▪ Surface degradation under UV-salt exposure (none / moderate / severe) ▪ Pollutant release (yes/no)
Bending performance in thin FDM sections Ability to undergo bending without brittle fracture.	▪ Relative bend tolerance (low / medium / high) ▪ Crack initiation under bending (early / late / none) ▪ Delamination under bending (yes/no)

Table 12.
Constraint-based evaluation of candidate materials for the Flexible Retention Component.

Material	Marine environmental compatibility	Bending performance in thin FDM sections	Evaluation
TPU	Water absorption: low–medium; Dimensional stability: minor change; UV-salt degradation: moderate; Pollutant release: no	Relative bend tolerance: high; Crack initiation: none; Delamination: no	**Pass**
PETG	Water absorption: low; Dimensional stability: stable; UV-salt degradation: moderate; Pollutant release: no	Relative bend tolerance: medium–high; Crack initiation: late; Delamination: no	**Pass**
ABS	Water absorption: medium; Dimensional stability: minor change; UV-salt degradation: severe; Pollutant release: no	Relative bend tolerance: medium; Crack initiation: early; Delamination: possible (yes)	**Fail**
ASA	Water absorption: low; Dimensional stability: stable; UV-salt degradation: none–moderate; Pollutant release: no	Relative bend tolerance: medium; Crack initiation: moderate; Delamination: possible (yes/no depending on print)	**Fail**
Nylon (PA)	Water absorption: high; Dimensional stability: unstable; UV-salt degradation: moderate; Pollutant release: no	Relative bend tolerance: high; Crack initiation: late; Delamination: no	**Fail**

Comments

The screening prioritized materials capable of bending in thin FDM sections (0.5–1 mm) without brittle fracture or delamination, while maintaining acceptable short-term marine stability. TPU and PETG met these requirements, showing high to medium–high bending tolerance with late or no crack initiation.
ABS and ASA were excluded due to early crack formation and potential interlayer failure under flexion.
Nylon (PA), despite good bending performance, was discarded because high water absorption leads to dimensional instability in marine conditions.
Consequently, only TPU and PETG satisfied both environmental and bending constraints.

Therefore, a ranking based on the defined objectives becomes necessary to support final material selection.

7.3 Flexible Retention Component

Objectives — **Parameters**

Controlled step-wise bending behavior
Preference for materials that allow progressive deformation under load with limited elastic springback, reducing the risk of continuous closing force against the growing holdfast.

- Elastic recovery after deformation (low / medium / high)
- Restoring force under bending (low / medium / high)

Availability / Cost-efficiency
Degree to which the material is accessible and economically viable for rapid prototyping.

- Filament availability (high / medium / limited)
- Cost per kg (low / medium / high)
- Ease of printing (high / moderate / difficult)

Table 13.
Objectives-based ranking of candidate materials for the Flexible Retention Component.

Material	Controlled step-wise bending behavior	Availability / Cost-efficiency	Ranking
TPU	★ Elastic recovery: high Restoring force: high	★★ Filament availability: high Cost per kg: medium–high Ease of printing: difficult	2º
PETG	★★ Elastic recovery: medium Restoring force: medium	★★★ Filament availability: high Cost per kg: low–medium Ease of printing: high	1º

Results

While TPU exhibits high deformability, its high elastic recovery and restoring force may generate continuous closing pressure, potentially opposing the slow biological growth required to trigger step-wise opening.

In contrast, PETG demonstrates moderate elastic recovery and lower restoring force, supporting more controlled progressive deformation under load. Additionally, PETG presents higher ease of printing and lower cost, reinforcing its suitability for iterative prototyping. Consequently, PETG was ranked as the preferred material for further development, with TPU retained as a secondary alternative.

Therefore, **PETG** is selected for the fabrication of the Flexible Retention Component using FDM-based rapid prototyping processes.

The material selection for the flexible retention component focused on bending performance in thin FDM sections and controlled elastic recovery. Flexural behavior, crack initiation, and interlayer delamination were evaluated based on polymer mechanics and additive manufacturing literature (Callister & Rethwisch, 2018; Tymrak et al., 2014; Torrado & Roberson, 2016). Elastic recovery of thermoplastic elastomers and moisture absorption under marine exposure were informed by specialized references and standardized testing frameworks (Holden et al., 2005; Osswald & Menges, 2012; ASTM D570; Gewert et al., 2015).

8. Prototype Development

This chapter presents the iterative prototyping process through which the system's components were tested, adjusted, and consolidated. By confronting material behavior, fabrication constraints, and assembly performance in real production contexts, the design evolves from conceptual controlled experimental configurations toward a technically grounded and buildable restoration system.

8.1 Prototyping Strategy

The prototyping phase was conceived as an iterative process oriented toward the progressive development of a functional system intended for real-world application beyond the temporal scope of this thesis. While exploratory in nature, this phase was not limited to open experimentation; instead, it aimed to progressively reduce uncertainty and converge toward a viable final configuration.

Consistent with a *research-through-design approach*, prototyping functioned as a mode of inquiry in which material behavior, fabrication constraints, and geometric performance **generated situated knowledge.** Physical iterations revealed performance thresholds that could not be fully predicted through theoretical evaluation alone, particularly in thin-section bending, mold-based casting, and press-fit integration.

Each prototype was designed to test specific variables (including material response under flexion, dimensional tolerances, casting feasibility, and assembly interaction) allowing incremental refinement of the system. Through this process, design decisions were informed by **direct material feedback**, supporting a transition from conceptual configuration to **technically grounded implementation.**

Prototyping activities were conducted across two fabrication environments. Initial iterations were developed at *La Fabrique*, the fabrication facility of **CentraleSupélec (Paris)**, which provided access to digital manufacturing tools and mold production equipment during a relocation period. Subsequent refinements and material casting tests were carried out at the *Industrial Design Prototyping Laboratory* of **Universidad del Bío-Bío (Chile)**, within the framework of the ongoing academic collaboration. The availability of these facilities enabled iterative testing across different material systems and fabrication scales.

[la fabrique]
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8.2 Textured Anchorage Core



Figure 35: Iterative prototyping of the Textured Anchorage Core, documenting mold refinement, material adjustments, drying times, and casting outcomes. (author's own elaboration).

Version 0.3 1c:0.5ls:2s	Results 5 days drying





Results

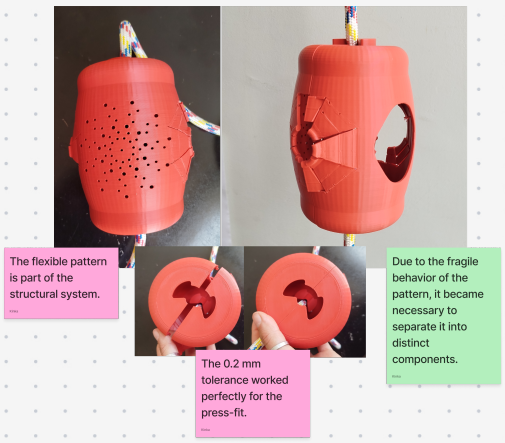
The prototyping phase directly informed the refinement of the final design, particularly regarding overall dimensions and manufacturability. Initial iterations at a height of 300 mm **revealed significant challenges in handling, casting, and demolding**, as well as practical difficulties during on-site implementation. To improve manageability and fabrication control, the component height was reduced to 150 mm, resulting in a **more feasible and robust configuration.**

The mold system also evolved through successive iterations. The number of mold divisions was progressively adjusted until an **optimal balance between geometric fidelity and demolding ease** was achieved. A configuration of 10 mold segments proved most effective, significantly facilitating extraction while preserving structural definition. Additionally, the draft angle was optimized to 1,5°, further **improving demolding performance** without compromising form accuracy.

Material formulation was similarly refined. Variations in cement proportion were tested to **enhance mixture homogeneity and casting consistency**. The final composition (1 part cement : 0.5 limestone : 2 parts sand) provided improved workability, structural integrity, and surface coherence. Together, these adjustments demonstrate how prototyping functioned as a decision-making framework, guiding dimensional, geometric, and material optimization toward a technically viable final configuration.

8.3 Protective Shell & Press-fit Connector

Version 0.1 Integrated Flexible Pattern	Version 0.2 Assambled Flexible Pattern





Results

The development of the Protective Shell revealed that integrating the flexible pattern directly into the main structure was **not feasible due to its fragility and printability limitations**. As a result, the design was iterated toward a **modular configuration** in which the flexible pattern could be manufactured as a separate component and subsequently assembled into the shell. This adjustment improved structural reliability while preserving the intended functional behavior.

Additionally, press-fit tolerances were tested to ensure secure yet feasible assembly. On the first try it was demonstrated that a tolerance of 0.2 mm provided the optimal balance between firm **mechanical retention and ease of insertion**, informing the final dimensional configuration of the assembly system.

Figure 36: Iterative prototyping of the Protective Shell and Press-fit Connector, documenting the transition from integrated to modular flexible patterns and tolerance calibration for reliable assembly (author's own elaboration).

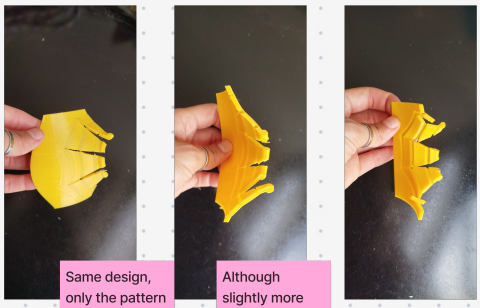
8.4 Flexible Retention Component

Version 0.1
Integrated Pattern PLA



It proved to be highly fragile due to both geometry and material.

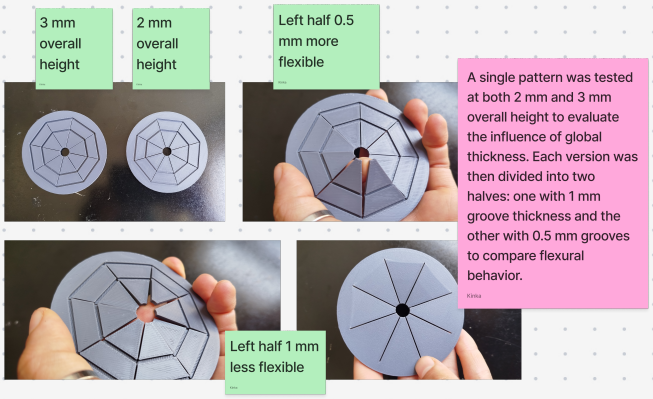
Version 0.2
Integrated Pattern PETG



Same design, only the pattern was tested. PETG.

Although slightly more flexible, it remains highly fragile.

Version 0.3
Pattern to assemble



Results

This prototyping phase showed that the fragility of the pattern was significantly affected by **printing orientation**. When printed perpendicular to the build plate, the grooves exhibited **early crack initiation and interlayer weakness under bending.** Printing the component parallel to the printer bed **improved structural continuity and reduced brittle failure**, resulting in more reliable flexural behavior.

Tests also indicated that a groove thickness of 1 mm provided the best balance between flexibility and structural integrity. Thinner sections (0.5 mm) proved too flexible, while 1 mm allowed controlled bending without premature cracking. These observations informed the final configuration of the flexible pattern.

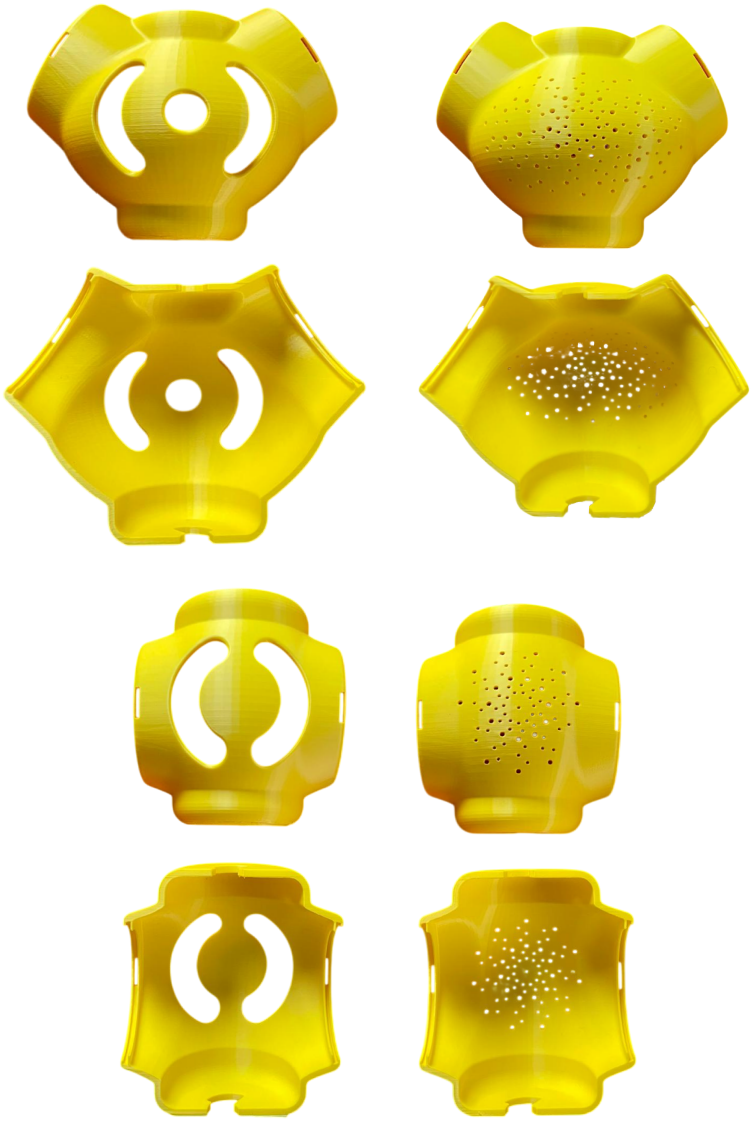
▶ **Figure 37:** Iterative prototyping of the Flexible Retention Component, evaluating material selection, print orientation, and groove thickness to achieve controlled bending performance (author's own elaboration).

9. System Consolidation

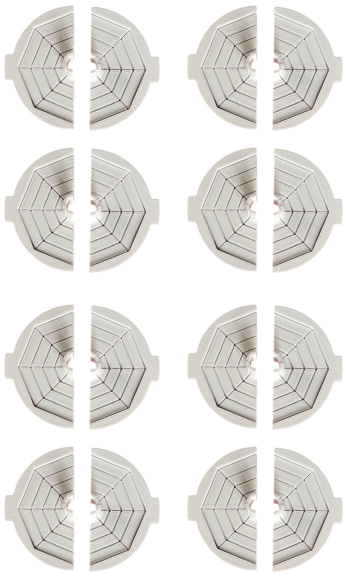
This chapter consolidates the project's final configuration, detailing its components, assembly sequence, and simulated deployment. The outcome reflects the integration of biological requirements, environmental constraints, material research, and prototyping feedback into a coherent, buildable restoration system conceived as an experimental infrastructure for kelp establishment.

9.1 System Components

- Protective Shells



- Flexible Retention Component



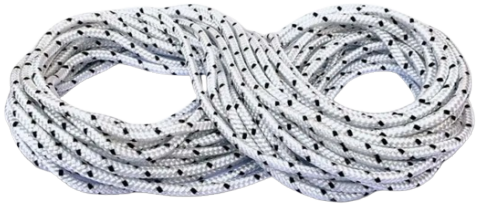
- Press-fit Connector



- Textured Anchorage Core

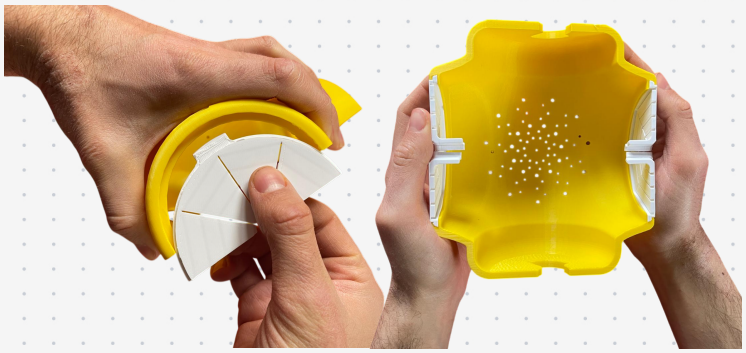


- Nylon Rope



▶ **Figure 38:** Final component set of the modular kelp restoration system (author's own elaboration).

9.2 Assembly and Installation Sequence



1 Insert the Flexible Retention Component into each Protective Shell.



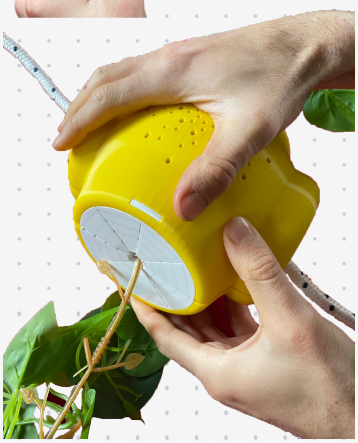
2 Insert the Textured Anchorage Core inside each Protective Shell.



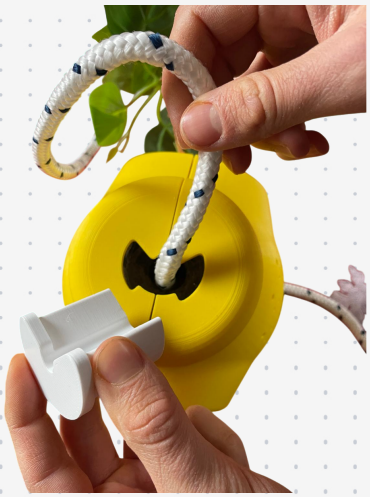
3 Pass the rope through the module.



4 Insert the juvenile algae into the Flexible Retention Components.



5 Close with the other half of the Protective Shell.



6 Join using the Press-fit Connector.



7 Tie the rope to the cultivation system line for installation.

Figure 39: Step-by-step assembly and installation process of the modular kelp restoration unit (author's own elaboration).

9.3 Simulated Deployment





Figure 40: Simulated suspended deployment of the modular kelp restoration system (author’s own elaboration).

10. Conclusions & Future work

10.1 Conclusions

This project demonstrated that design can operate as an **experimental, translational, and collaborative practice within marine ecological restoration.** Developed through a *research-through-design* methodology and grounded in a *situated case study* in Coliumo, the work showed that it is possible to construct material systems that do not aim to validate predefined hypotheses, but to generate conditions for learning from ecological processes in situ.

From a *more-than-human design* perspective, the research demonstrated that *Macrocystis pyrifera* can be approached as an active agent within the design process. Rather than designing for the algae, the project designed with its growth dynamics, treating holdfast expansion and mechanical interaction as formative forces capable of informing structural response.

Through iterative prototyping and *transdisciplinary collaboration* with marine biologists and local actors, the project demonstrated how **translational design can mediate between biological knowledge, engineering constraints, and material experimentation.**

The project demonstrated the feasibility of designing **temporary structural systems** specifically aligned with the ecological bottlenecks of early-stage establishment. While full ecological validation remains pending, the research established a coherent framework for adaptive, field-informed development in which **ecological feedback will guide future iterations.**

10.2 Future Research Directions

The next phase of this research involves the in situ installation of the developed modules in collaboration with researchers from Universidad del Bío-Bío. Field deployment will enable direct observation of the interaction between juvenile *Macrocystis pyrifera* and the controlled-opening system, particularly how holdfast growth and mechanical expansion influence structural response over time.

The resulting ecological feedback will be central to the continuation of the project. Observing how the algae engages with systems designed for progressive opening will **generate new knowledge about growth-driven mechanical interaction.** This understanding will **inform subsequent design iterations**, allowing the refinement of geometries and, more critically, the development of material strategies capable of supporting controlled opening while remaining environmentally compatible for long-term installation and replicability.

The continuation phase is currently linked to a joint funding application submitted with academic partners at Universidad del Bío-Bío. If granted, this support will enable systematic monitoring, long-term ecological assessment, and iterative redesign based on field-based evidence.



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