A Symbiotic Approach for Developing Shoreline Infrastructure

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Abstract. This research project presents an alternative approach to addressing the complex challenges of sustainability of the coastlines by integrating advanced technology solutions with ecological conservation principles. The paper introduces the Ecoblox, a modular infrastructure system consisting of interlocking blocks devised for attachment to seawalls to improve marine biodiversity at the water edge. The design of the Ecoblox system employs environmental data, data analytics, AI-powered generative algorithms, and digital fabrication to produce blocks with complex shapes and textures suitable for bio-marine habitats.

The project is executed in two phases. This paper describes the initial phase, encompassing the prototyping process, construction, testing, and analysis of various Ecoblox versions. The primary objective of this phase is to assess multiple designs and evaluate their effects on biodiversity. Building upon the insights gained from the initial phase, Phase II of the study focuses on developing data-driven strategies and applying robotic 3D printing to refine the system's design and construction.

Keywords: Symbiotic Intelligence · Coastal Architecture · AI-enhanced Design · Modular Shoreline Infrastructure · Ecoblox · Biodiversity Promotion · Climate Resilience · Ecosystem-Centric design · Environmental Sustainability · Robotic 3D Printing

1 Introduction

Climate change is the century's defining challenge (Rogelj et al. 2021; Masson-Delmotte et al. 2018), and the coastal regions are experiencing full impact. Rising sea levels are causing severe coastal erosion, excessive sedimentation, water contamination, frequent floods, hurricanes, severe storms, and storm surges (Azevedo de Almeida and Mostafavi 2016). In addition, rising ocean temperatures, one of the major consequences of climate change, poses a significant threat to marine ecosystems, leading to loss of biodiversity (Breitburg et al. 2018).

The widespread use of hard or gray infrastructures like concrete seawalls and barriers to mitigate coastal erosion has been detrimental to coastal ecosystems (Pilkey and Cooper 2012; European Environment Agency 2018). A NOAA study predicts that a third of the US coastline could be covered in concrete by 2100 (Dilling and Lemos 2011). Gray infrastructures damage natural habitats, exacerbating biodiversity loss in marshes,

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mangroves, and coral reefs (Worm et al. 2006; Arkema et al. 2013; Bulleri and Chapman 2010; United Nations Environment Program 2019, p. 45). Seawalls have reduced suitable nesting habitats for marine wildlife, decreasing their survival rates (Bulleri and Chapman 2010).

To address the problematic approach of using gray infrastructure, several innovative strategies have been implemented along the shorelines. Hybrid infrastructures, which integrate gray and green infrastructure, are gaining significant attention and are being implemented in several projects across the country (Maltby and Waldon 2018, Othman and Shaari 2021). Hybrid infrastructures sequester carbon while providing the same protection as seawalls and levees by combining plants and dunes. In addition, studies have shown that they can be an effective means of coastal protection while promoting biodiversity and ecosystem services (Melián-González et al. 2020; Kirshen et al. 2018).

A few successful projects in recent years have highlighted the potential benefits of hybrid infrastructures. For example, the Living Seawall project in Australia resulted in a 36% increase in biodiversity upon retrofitting seawalls with habitat panels (Dafforn et al. 2015; Campbell et al. 2019; Browne et al. 2019; Firth et al. 2016). Similarly, the Seattle Waterfront project used light-penetrating surfaces and biological stormwater management, allowing marine life like juvenile salmon to return to the shoreline (Dyson and Yocom 2014; Beekman 2019). A pilot study conducted during the project's early phase revealed that textured treatment of the seawall promoted microhabitats (Dyson and Yocom 2014).

While innovative coastal management approaches are essential, projects like the Living Seawall and Seattle Waterfront, which focus on creating complex textures conducive to marine habitat, represent limited strategies for enhancing biodiversity and sustainability of the shorelines. Emerging technologies such as networked sensors, big data analytics, parametric design algorithms, and robotic fabrication are introducing new possibilities for hybrid infrastructure design and construction. For instance, parametric design facilitates the creation of complex geometries based on optimization rules using AI, enabling the integration of various parameters such as site conditions and performance criteria (Wassim Jabi and Ozel 2017). Furthermore, robotic construction methods can be integrated with parametric design tools to generate complex, customized, and optimized geometries and forms.

This project builds on these recent technological innovations to create "Ecoblox," a modular interlocking system of blocks engineered for seawall attachment. Designed with specific geometries and textures, Ecoblox aims to foster ecological functionality by developing microhabitats that promote the colonization and growth of diverse marine organisms. The project's first stage, Phase I, which is elaborated upon in this paper, aims to establish a proof of concept for Ecoblox. Following this, Phase II is dedicated to refining the system through a data-driven methodology (Fig. 1).

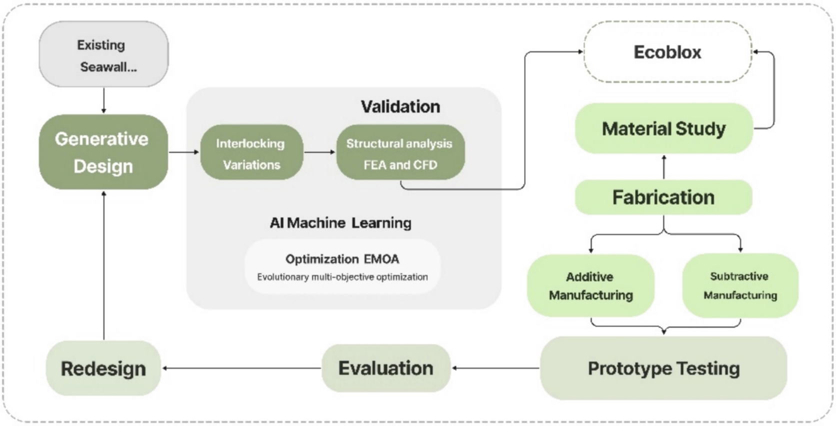

Fig. 1. Diagram describing the project development process.

2 Prototype Development: Phase I

In Phase 1 of the project, the key objectives were: 1) Conducting comprehensive research on factors influencing seawall and hybrid infrastructure design, including structural integrity, durability, and impact on biodiversity; 2) Collecting and analyzing data to inform the design and fabrication of textured surface prototypes. 3) Applying AI algorithms for optimization, enabling efficient and adaptive design iterations of the textured geometries; 4) Constructing and testing these prototypes in coastal waters to evaluate their performance in promoting biodiversity; 5) Conducting sustainability evaluations to assess the ecological impacts and biodiversity enhancement provided by the prototypes.

2.1 Fabrication

The fabrication process in this phase involved an iterative design workflow combining data analysis, parametric modeling, and digital fabrication techniques. This allowed us to explore various designs and rapidly produce physical prototypes for in-situ testing. A key focus of the fabrication approach was developing various surface textures to evaluate their influence on biodiversity. We hypothesized that creating distinctive biomimetic textures inspired by natural marine habitats like coral structures, Ecoblox surfaces would provide favorable microhabitats and enhance biodiversity.

An experimental arrangement was created to evaluate this hypothesis. We designed prototypes inspired by two natural patterns. The Voronoi pattern emulated the intricate structure of honeycomb coral, and the reaction-diffusion pattern drew from the complex folds of brain coral. The patterns designed for the blocks were digitally decoded using Grasshopper, a visual programming tool, and then precisely transferred onto the block surfaces using a CNC milling machine. This process detailed the patterns onto a flexible foam, which acted as molds for the casting. In addition, we experimented with various concrete mixes with lower cement content to decrease the carbon footprint of blocks.

The subsequent pouring of concrete mixes into molds resulted in prototypes measuring $1' \times 2' \times 2''$, displaying three unique designs: flat, honeycomb coral, and brain coral.

Five concrete prototypes featuring two distinct surface textures and three different concrete mixtures were placed in an intertidal zone. Additionally, a control prototype block with no surface treatment was produced to serve as a benchmark for comparative analysis with the textured prototypes. The prototypes were left undisturbed for two years, allowing for an extended data collection period. This duration was crucial for a thorough analysis of the tiles' effectiveness (Fig. 2).

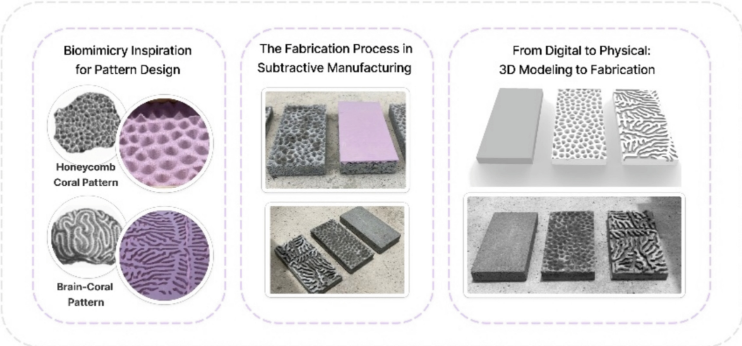

Fig. 2. The sequence of images showing the stages of creating prototypes: digital designs for honeycomb and brain coral patterns, their CNC-milled foam molds, and the final concrete prototypes, including a flat control tile.

2.2 Data Collection and Analysis

The ecological dynamics of the prototype were evaluated using a comprehensive data collection process, which included counting attached invertebrates and photographing and scanning the blocks to assess algae coverage. This analysis revealed the growth of

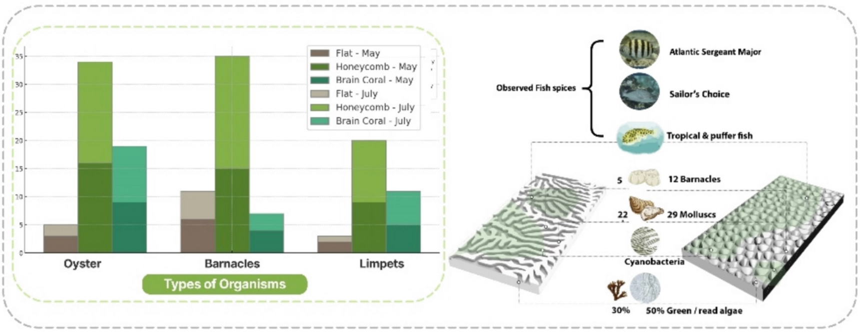

Fig. 3. Bar chart and the diagram showing the invertebrates count in 3 months.

three species of oysters, barnacles, and limpets on the textured blocks, whereas the flat control block exhibited negligible growth. The bar chart in Fig. 3 provides a detailed account of the results recorded over three months.

The analysis results demonstrated that surfaces featuring enhanced texture and rugosity significantly boosted natural growth, setting the stage for the project's next phase (Fig. 4).

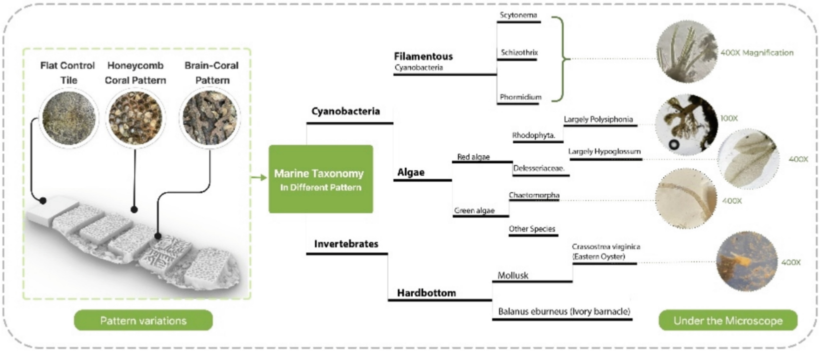

Fig. 4. Marine taxonomy for growth on Ecoblox

3 Prototype Optimization: Phase II

In Phase 2, which is currently underway, the project will focus on leveraging robotic 3D printing to construct the interlocking system for the blocks in a sustainable way. In addition, AI-driven generative optimization, utilizing environmental data sets, will enhance the blocks' texture and improve their structural integrity. Incorporating local data, such as solar radiation and air and water temperatures from the block's deployment site, will inform the design of new types of patterns and textures. These data-driven patterns could offer significant thermal stress relief for marine invertebrates and more accurately designed habitats for marine species.

Using robotic 3D printing to construct the blocks presents multiple benefits. First, it facilitates the fabrication of complex geometries with control over material distribution. Second, it allows the development of the Ecoblox without the formwork required for casting, a potentially waste-free process. Lastly, it will enable the exploration of various concrete mixes and sustainable alternative materials in the printing process (Fig. 5).

3.1 Interlocking System

To develop the interlocking system for the blocks, the project builds on a methodology introduced by Estrin et al. in 2021. This methodology explores a design principle that focuses on structuring material into interlocked elements without needing connectors or binders, purely based on their geometry and mutual arrangement. This approach

Fig. 5. Proposed design process in Phase II

draws inspiration from natural growth processes, mirroring the complex yet orderly development observed in biological and geological formations (Estrin et al. 2021).

To develop the interlocking system, we will employ lofting algorithmic operations. Specifically, our approach integrates a growth-based design algorithm inspired by Voronoi tessellation to design space-efficient, structurally robust shapes exhibiting superior directional interlocking. This innovative design methodology facilitates the creation of components that offer enhanced flexibility and strength, which is particularly advantageous in withstanding multidirectional or unpredictable loads, which is typical at the water's edge.

We plan to use Finite Element Analysis (FEA) software to model the edge geometries, enabling a detailed examination of how different edge conditions affect the overall strength and stability of the interlocking system. FEA will allow us to incorporate the material properties of concrete for various types of 3D printed infills inside the blocks. The analysis results will provide insights into the concrete's behavior under simulated loads, including cracking and other failure mechanisms (Fig. 6).

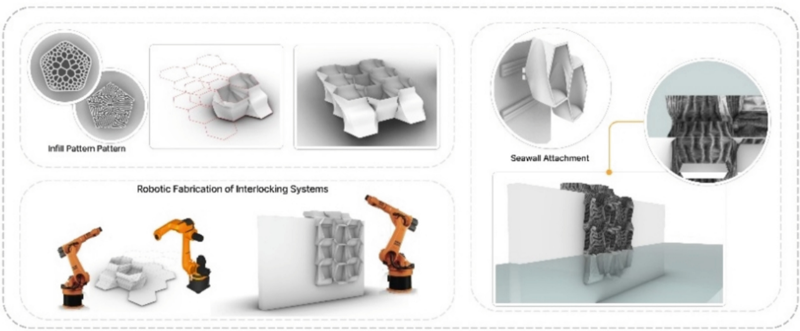

Fig. 6. Illustration of interlocking systems for seawall attachment

3.2 Testing and Evaluation

The Ecoblox prototypes' testing and biodiversity evaluation will involve their placement across different site locations, each characterized by unique water conditions, mainly varying salinity levels. This critical task aims to assess the prototypes' effectiveness and identify any areas of failure. The findings from these tests will inform necessary adjustments and enhancements to the prototype designs.

We will monitor and measure the growth of benthic communities, including macroalgae, sponges, mollusks, and barnacles on the prototype surfaces. These organisms obtain their nutrition by filtering and extracting organic particles from the water in their surroundings. This evaluation will ascertain the blocks' effectiveness in attracting marine life and enable us to gauge their impact on mitigating water pollution in the surrounding area.

4 Closing Remarks

As climate change and coastal erosion continue to present formidable challenges to global ecosystems, developing innovative approaches to coastal development and seawall construction is imperative. Advanced technologies, including Artificial Intelligence (AI), sensor technologies, big data analytics, and robotic manufacturing, are bringing new possibilities for data-driven approaches to the built environment. Through informed design, these approaches can help minimize ecosystem harm and promote sustainable development.

The Ecoblox system described here aims to offer a new perspective on coastal design, emphasizing support for biodiversity, enhancing climate resilience, and promoting environmental sustainability. This system's successful implementation and validation promise to catalyze a shift toward ecosystem-centric infrastructure design.

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References

Arkema, K.K., et al.: Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Chang. **3**(10), 913–918 (2013). https://doi.org/10.1038/nclimate1944

Azevedo de Almeida, B., Mostafavi, A.: Resilience of infrastructure systems to sea-level rise in coastal areas: impacts, adaptation measures, and implementation challenges. Sustainability **8**(11), Article 1115 (2016)

Beekman, G.: See the new $7.1 million shortcut to Seattle's waterfront. The Seattle Times (2019). Retrieved from https://www.seattletimes.com/seattle-news/politics/see-the-new-7-1-million-shortcut-to-seattles-waterfront/

Breitburg, D., et al.: Declining oxygen in the global ocean and coastal waters. Science **359**(6371), eaam7240 (2018). https://doi.org/10.1126/science.aam7240

Browne, N., Smith, J., Jones, A., Green, D.: Enhancing biodiversity through living seawalls: a case study of habitat panels in Australia. J. Mar. Biol. Conserv. **15**(3), 245–256 (2019)

Bulleri, F., Chapman, M.G.: The impact of artificial structures on marine ecosystems. Mar. Environ. Res. **70**(5), 365–377 (2010). https://doi.org/10.1016/j.marenvres.2010.05.002

Bulleri, F., Chapman, M.G.: The introduction of coastal infrastructure as a driver of change in marine environments. J. Appl. Ecol. **70**(5), 365–377 (2010). https://doi.org/10.1111/j.1365-2664.2009.01751.x

Campbell, M.L., Bishop, M.J., Mayer-Pinto, M.: Living seawalls: Biologically active artificial structures can enhance the biodiversity and ecological functioning of urban seascapes. Front. Ecol. Evol. **7**, 1–13 (2019). https://doi.org/10.3389/fevo.2019.00234

Dafforn, K.A., Glasby, T.M., Airoldi, L., Rivero, N.K., Mayer-Pinto, M., Johnston, E.L.: Marine urbanization: an ecological framework for designing multifunctional artificial structures. Front. Ecol. Environ. **13**(2), 82–90 (2015). https://doi.org/10.1890/140050

Dilling, L., Lemos, M.C.: Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Chang. **21**(2), 680–689 (2011). https://doi.org/10.1016/j.gloenvcha.2010.11.006

Dyson, K., Yocom, K.: Ecological design for urban waterfronts. Urban Ecosyst. **18**(1), 189–208 (2014). https://doi.org/10.1007/s11252-014-0385-9

European Environment Agency.: Coastal erosion and climate change in Europe (2018). Retrieved from https://www.eea.europa.eu/publications/coastal-erosion-and-climate-change-in-europe

Estrin, Y., Krishnamurthy, V.R., Akleman, E.: Design of architectured materials based on topological and geometrical interlocking. J. Market. Res. **15**, 1165–1178 (2021)

Firth, L.B., et al.: Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. Oceanogr. Mar. Biol. Annu. Rev. **54**, 189–262 (2016)

Kirshen, P., Ruth, M., Carbone, G.: Hybrid infrastructure and its role in improving resilience to climate change. Environ Sci Policy **86**, 76–84 (2018)

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Waterfield, T.: Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming. **1**, 93–174 (2019)

Maltby, E., Waldon, M.G.: Integrating gray and green infrastructure for water management: a review of concepts and research. J. Environ. Manage. **221**, 324–334 (2018). https://doi.org/10.1016/j.jenvman.2018.05.066

Melián-González, S., Mendez, F.J., Losada, I.J., Torres-Navarro, G.: Hybrid coastal protection: a review of the main concepts, designs, and ecological effects. J. Clean. Prod. **260**, 121131 (2020)

Othman, N., Shaari, N.: An overview of green-gray infrastructure integration as an urban flood management solution. Environ. Sci. Pollut. Res. **28**(2), 1197–1215 (2021). https://doi.org/10.1007/s11356-020-10832-9

Pilkey, O.H., Cooper, J.A.G.: Society's choices: mitigating the impacts of climate change on the coasts. National Academies Press, Washington, DC (2012)

Rogelj, J., et al.: Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: IPCC (Ed.), Global Warming of 1.5°C. Cambridge University Press (2021)

United Nations Environment Programme.: Global environment outlook: Summary for policymakers (2019). Retrieved from https://www.unep.org/resources/report/global-environment-outlook-6-summary-policy-makers

Wassim, J.E., Ozel, F.: Robotic Fabrication in Architecture, Art, and Design 2016. Springer International Publishing, Cham, Switzerland (2017). https://doi.org/10.1007/978-3-319-58487-9

Worm, B., et al.: Impacts of biodiversity loss on ocean ecosystem services. Science **314**(5800), 787–790 (2006). https://doi.org/10.1126/science.1132294