Designing Bio-Shelters: Improving Water Quality and Biodiversity in the Bays Precinct through Dynamic Data-Driven Approaches

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Abstract: The Bio-Shelters project applies advanced computational methods utilised by architects to design green coastal landscape infrastructure intended for threatened marine ecosystems. Nature's logic is adapted to create colonies of species other than human. Advanced computation is applied to design 3-dimensional seawall structures supporting ecologically important marine organisms at urbanised coastlines. The project aims to enhance the abundances of native habitat-forming organisms, which are often missing or found in low numbers due to environmental degrading. This paper presents the results of this study, by also revisiting key moments and challenges met and compared along its way.

Keywords: Data-driven, integrated landscape design, simulation, sustainability, material research.

1 Introduction

In recent design research, computation has been employed in architecture to approach higher levels of complexity. Holistic approaches can be assisted by data-driven input/output processes offering comprehensive solutions for the landscape and the artificial milieu in meeting ecological challenges on nature's terms. From a practical point, nature's structures are set by criteria and parameters that describe its operations. The results of such dynamic approaches are more responsive to natural constraints. To that end, computing is an intellectual and a technical platform whereat influences of any kind may be brought together as variables and approximated in simulation models producing alternative solutions. The outcome of such computational approaches can be controlled with regards to the initial goals.

The present case focuses on the development of artificial seawall structures inviting threatened species in urban coastal landscapes. The rapid urbanisation of coastal areas has often caused shrinking of the population and even extinction of native marine species whose presence has been vital for the environment's sustainability and balance. A team of cross-scientific experts was established, which included architects, marine biologists, environmental and material scientists, designers and artists. Collaboration was possible via a multi-faceted computational platform that facilitated communication, data management and filtering across different scientific areas and above all the execution, iterative testing, enriching and updating of the findings at each step. This paper presents the above research and its main results.

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2 Cross-Scientific Inputs Informing Design

2.1 Biological Data and Targeted Design Goals

For the Bio-Shelters project it was important first to collect information related to the biological needs of key habitat-forming species, then to translate these inputs into ones that are meaningful to design decisions. The habitat requirements were studied by an extensive literature research, then they were codified as typological, organisational and morphological inputs generally applicable in architecture, this time for the development of alternative schemes. Species were selected from a list of common sessile (non-moving) and mobile species found in Sydney Harbour (HUTCHINGS et al. 2013). Marine biology experts within the group focused on organisms known to be found on natural rocky shorelines at and near the site where the Bio-Shelters will be deployed. The sessile species were then assigned into two main functional groups: 1) filter-feeders and 2) algae. Filter-feeders, which included oysters, mussels, barnacles and a polychaete (subtidal and intertidal), improve water quality (COEN et al. 2007; GRABOWSKI et al. 2012; ARMBRUSTER 2018) and increase biodiversity by creating habitat for other organisms (BARNES 2003, JACKSON et al. 2008). Algae, which included both intertidal and subtidal species, also serve as habitat for mobile species (MIGNÉ et al., 2015, POORE & LOWRY 1997), provide carbon sequestration benefits (KRAUSE-JENSEN & DUARTE 2016) and can mitigate environmental stressors in the intertidal zone (BERTNESS et al. 1999). The literature research included a variety of snails, limpets, a seastar and a fish. Mobile species found on natural rocky shores are often rare or absent on artificial structures (CHAPMAN 2003). The selected organisms improve the water quality along urbanised coastlines.

The research produced qualitative and quantitative data for use in the Bio-Shelters models. Variables included, but were not limited to, general information about the species such as size, distribution or recruitment season, information about biotic interactions (competition, predation) with other species, environmental data on tolerances to temperature, salinity, water loss, sedimentation and water quality, distribution on the shore (tidal/water depth, wave actions), as well as light, substrate and other habitat requirements. However, not all information was available for every species. Although some of the variables (i. e. salinity, water quality) are set by the environmental conditions and cannot be manipulated with the design, these variables were used to determine which species are likely to colonise the site.

The next step was to incorporate the information gathered into the computational model. The findings were transformed into categories or binary data for most variables (e. g. desiccation tolerance → can survive out of water: yes/no). Then, focus was given to the variables that are paramount for the survival of the species, suggested as design parameters for the Bio-Shelters schemes set with regards to different habitats and site conditions. These included water flow (for filter feeders), light and water supply (to prevent desiccation) for algae, and access to food and shelter from environmental stressors for mobile species. This can be achieved by limiting shading through appropriate form and orientation decisions, also by allowing water flow through gaps and voids into the structure for circulation and through the addition of refuges such as water-retaining pool features and small shaded areas. Shaded spots were kept to a minimum to avoid settlement of invasive species, which favour shaded areas (DAFFORN et al. 2012, MILLER & ETTER 2008). Species were then grouped according to their vertical distribution on the shore landscape as subtidal, low-, mid-, and/or high intertidal, and the design of each zone was matched to the species habitual needs (CHAPMAN 2003, SCHAEFER et al. 2018). Transition zones were included to ensure a smooth change from one zone to another. Surface structure was included whenever possible, by noting however that in the final design such areas would be smaller due to structural limitations related to own weight, the manufacturing process and material testing. Information on recruitment season was also suggested to determine optimal deployment of the Bio-Shelters to facilitate colonisation by target species.

2.2 Quest on Materials for Nature-Compliant Seawall Structures

Following related studies on materials for waterfront structures (MARCUS et al. 2016), a literature review and meta-analysis was used to compare recruitment of native species between natural (e. g. wood, shell, rock) and artificial (e. g. concrete, PVC) materials. Metrics included species richness, abundance in different functional groups, density and abundance of key habit-forming taxa of invasive species. The research revealed that there was no difference in total species richness, abundance or cover between natural and artificial materials, but there was significantly greater invasive species richness and cover on artificial ones. Total species abundance varied among material types and was generally higher on Perspex and lower on PVC, plexiglass, fiberglass, metal and porcelain compared to natural materials. Concrete, acrylic, brick, fiberglass, glass, plastic, PVC, rubber, metal Perspex and steel supported similar species abundances to natural materials. Additional research suggests that selection of high pH materials can help to mitigate the impacts of ocean acidification on associated species. Under scenarios of acidification and warming, sea urchins that settled on higher pH concrete grew larger, had longer spines and greater survivorship than those that settled on lower pH granite or greywacke (MOS et al. 2019). Furthermore, cover of algal turf was greater on concrete than on granite or high-density polyethylene under scenarios of ocean acidification and increased temperature (DAVIS et al. 2017). Concrete also has the benefit in the Sydney region of providing settlement cues for the native rock oyster (ANDERSON 1996).

2.3 Site Specific Design

This project uses modelling techniques more usually linked with architectural methods. As a start, coastal habitats are under threat from rapid urbanisation. In some estuaries including Sydney Harbour, over 50 % of the shoreline has been hardened by coastal defenses such as seawalls (DAFFORN et al. 2015) supporting a greatly reduced native biodiversity and ecosystem services than rocky reefs (CHAPMAN 2003). This is because seawalls are typically flat, featureless, 2D structures lacking microhabitats such as rockpools and crevices. Green or eco-friendly artificial habitats may enhance the native biodiversity and the ecological value of seawalls along heavily urbanised coastlines. Previous approaches to green engineering have typically identified habitat features (i. e. rockpools, crevices) missing from seawalls and added these using additive (i. e. retrofit) or subtractive (i. e. drilling) approaches. Such approaches assume that these habitat features will function similarly on artificial structures as in natural habitats, despite the large environmental differences. However, in contrast to interventions of seawalls suggesting repeated 2D habitat tiles the Bio-Shelters project provides customised 3D structures in response to its habitant's needs as a critical improvement to attract more suitable species and cause more rapid colonisation and population restoration.

The Bays Precinct of Sydney Harbour was chosen as the Bio-Shelters' test site. Sydney Harbour is an area of remarkable biodiversity but has been heavily modified by a multitude of historical and contemporary human pressures. The area west of the Harbour Bridge in which the Bays Precinct is found, has poor water quality, high levels of heavy metal pollution and microplastics, with much of the natural rocky reef habitat replaced by seawalls (DAFFORN et al. 2012, MONTOYA 2015). Despite environmental degrading, a variety of habitat forming species (e. g. barnacles, oysters, seaweeds) are able to persist on the remnant rocky shores of the harbour, forming complex habitat structures for other animals and seaweeds (Figure 1), and cleaning water through filter feeding and removal of excess nutrients and heavy metals.

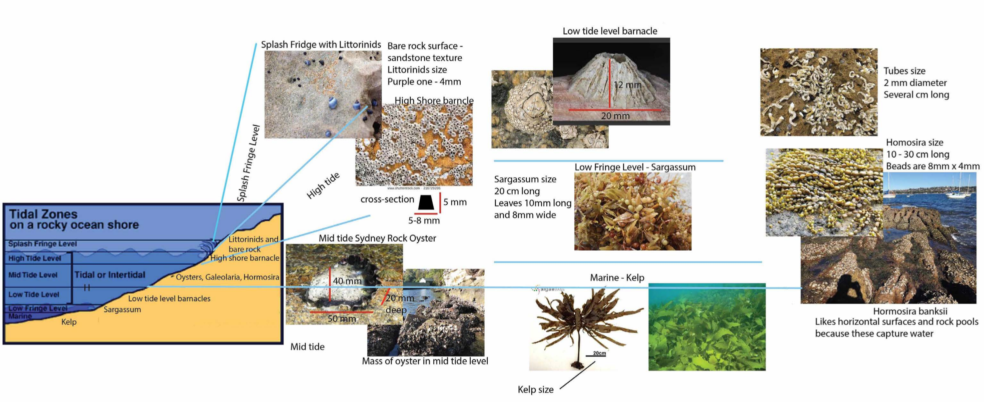


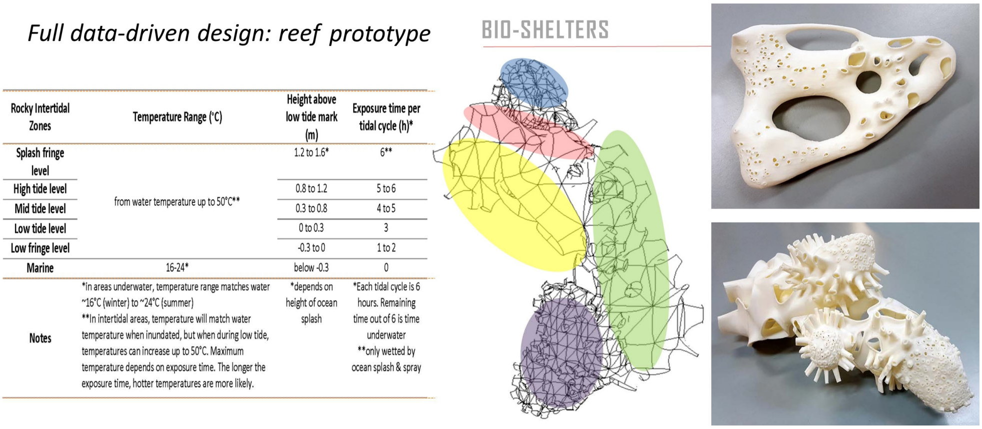
Fig. 1: Typical natural shoreline showing the key-habitat forming organisms

Meanwhile, the repeated seawalls commonly developed are generally stressful environments for many of these key-habitat forming species because they typically lack microhabitats that protect them from predation and environmental stressors such as drying at low tide. The Bio-Shelters project aims to ameliorate such stressors and pressures so that desirable species can develop resilience and thrive as in their natural environments. As in architectural applications, biological data were collected describing the living conditions of various inhabitants, also contextual information concerning seascape, site topography, water temperature and currents. The produced datasets established an iterative process leading to site and organism-specific design outcomes. Parameters influencing the viability of marine species such as bivalves and seaweeds were translated into design structures and then prototyped.

3 Design Modelling Engineered by Computing

Biological and material inputs along with site-specific information form design parameters and ought to be included in the computational design model. The aim has been to employ data-driven approaches supported by scripting and dynamic simulations throughout the whole process. Specifically, the project applies advancements in computation to marine datasets, by which to generate an number of design outcomes (seawalls, reefs) with reference to the site and water quality (ZAVOLEAS & HAEUSLER 2017). Autodesk Maya was the main platform to develop the script given its advanced modelling features and ability to simulate dynamic inputs through particles, also material behaviours and a good approximation of physics through forces, fields and collisions. On a different focus, it has been assumed that the results better respond to environmental requirements if they incorporate sustainable materials for the fabrication process. The designs may be physically produced through digital fabrication processes, linked with analysis and the computational model through automated and scripted procedures. Information about natural rocky reefs and seawalls has been a critical factor in shaping the script, so that the produced schemes would be linked back to the needs of different organisms, environmental conditions, and the site. The Bays Precinct area was the first case study to test the script, with the potential to expand to other urbanised costal sites. The inputs were organised with regards to macro-, meso- and micro- dimensions:

- macro – responds to site location (geospatial data): positioning, orientation, exposure to sun/wind, wave impact, topography, and material consistency of the shoreline;
- meso – sets the habitat requirements of barnacles, oysters, mussels, kelps, canopy-forming / branching coralline algae, forming the typological features, and microclimate (Figure 2);
- micro – refers to material composition. For higher compatibility and efficiency, the project uses a mixture of concrete/crushed oyster shells.



Full data-driven design: reef prototype

Rocky Intertidal Zones	Temperature Range (°C)	Height above low tide mark (m)	Exposure time per tidal cycle (h)*
Splash fringe level	from water temperature up to 50°C**	1.2 to 1.6*	6**
High tide level		0.8 to 1.2	5 to 6
Mid tide level		0.3 to 0.8	4 to 5
Low tide level		0 to 0.3	3
Low fringe level		-0.3 to 0	1 to 2
Marine	16-24*	below -0.3	0
Notes	*in areas underwater, temperature range matches water ~16°C (winter) to ~24°C (summer) **In intertidal areas, temperature will match water temperature when inundated, but when during low tide, temperatures can increase up to 50°C. Maximum temperature depends on exposure time. The longer the exposure time, hotter temperatures are more likely.	*depends on height of ocean splash	*Each tidal cycle is 6 hours. Remaining time out of 6 is time underwater **only wetted by ocean splash & spray

Fig. 2: Data-driven design process with different physical outcomes in miniature size

The first designs were prototyped as miniatures with PLA filaments using 3D printing and CNC milling (Figure 3). Then, one model was scaled up and built with a Z-corp printer and ABS material. The aims were then reset for physical size and compatible materials.

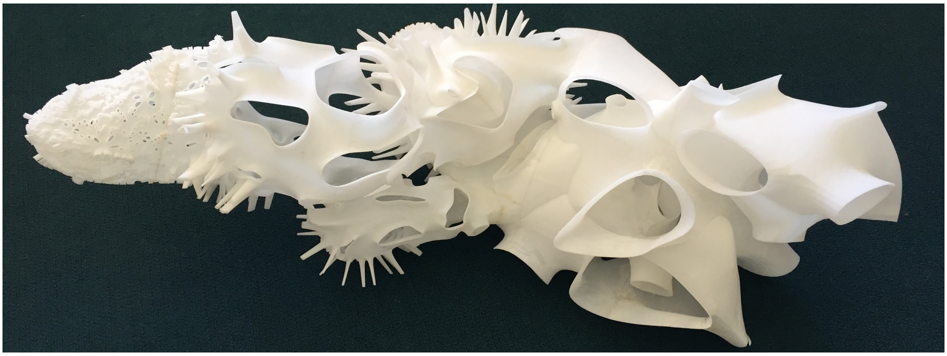


Fig. 3: 3D printed model in PLA as prototype

This set of tests involved printing larger forms out of clay (TRILSBECK et al. 2019). Clay is well suited to artificial reef and seawall habitats (RAEL et al. 2018), but its response to complexity was unpredictable. Consequently, a set of hybrid digital-analogue crafting tests were made to turn complex form into clay outputs (Figure 4). These attempts would be pursued in detail across data integration, materiality and fabrication as the next challenges (Figure 5).

Fig. 4: 3D clay printed model

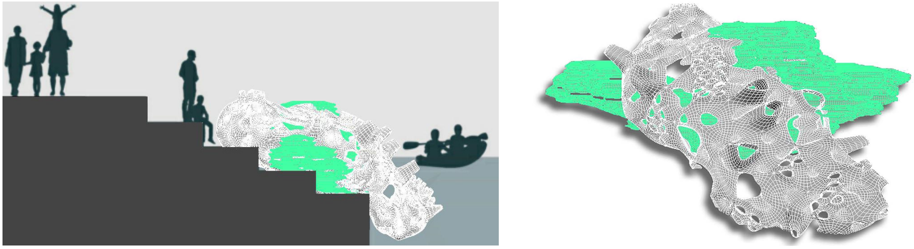


Fig. 5: Design scheme incorporating site-specific data. Section by 3XN architects

4 Material Tests and Large-Scale Prototypes

4.1 Material Tests

A pilot experiment was undertaken to assess the optimal material type, and macro- and micro-texture. It had two factors, material composition (which also influenced micro-texture) and the presence or absence of pits and mounds. Performance criteria were the corrosion of tiles and their colonisation by native species. The trial was based around the use of concrete. Concrete can be produced at scale, has had significant testing in marine conditions, does not need firing, and can be easily altered (DUNN et al. 2019). The material mixes were:

1) a standard concrete mix of 2-parts cement: 1-part sand: 2-parts crushed rock aggregate;
2) a vermiculite treatment, with 2-parts cement: 1-part sand: 1-part vermiculite, 1-part crushed rock aggregate;
3) an oyster treatment, with 2-parts cement: 1-part sand:1-part sustainably-sourced crushed oyster shells, 1-part crushed rock aggregate.

All treatments had the same standard concrete base mix, with treatments 2 and 3 also including an additive. Vermiculite (hydrated laminar magnesium-aluminum-iron silicate) is a porous, lightweight material that was investigated due to its potential to reduce the weight of the concrete structures, add texture and anchor points for different species to attach to. Oyster shell was tested as an additive because it encourages recruitment of live oysters (Zimme-Faust & Tamburri 1994), which in turn provide food and habitat to other associated species. Oyster shells were sourced from the Sydney Fish Market, crushed with a Rock Crushing Machine and a Ball Mill, then sieved through a mesh sieve. Sixty 200 × 200 × 50 mm tiles were produced and placed into the water. The tiles were mounted on a steel mesh frame and submerged vertically into the intertidal zone at Blackwattle Bay, Sydney to test the structural integrity of the material in marine conditions and the interaction with marine life (Figure 6).

Fig. 6: The tiles attached to frames prior to deployment from a jetty in Blackwattle Bay. Tiles were randomly arranged on frames then and all frames were hung in the intertidal zone.

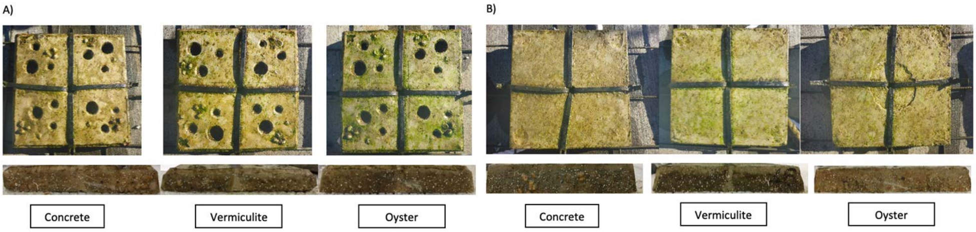


Fig. 7: Images of the tiles 6 weeks after deployment, A) of complex tiles; B) of flat tiles

Thirty tiles were collected from the ocean after 6 weeks (Figure 7). Photos were taken to assess percent cover of fouling organisms on the vertical outward facing surface and the horizontal downward facing surface. Overall there were more green and brown filamentous algae on the vertical outward face and more invertebrates on the horizontal downward face (including oyster recruits and the non-indigenous species *Styela plicata*, *Bugula neritina*, *Bugula flabellata*, *Schizoporella errata*, and *Diplosoma listerianum*). No obvious differences were observed among materials or complexities. The remaining tiles are monitored for a longer period to get a better sense of their performance and behaviour at the intended context.

Next, another prototype model was produced, a 500 × 500 mm section of the custom computationally designed script at 1:1 scale intended for onsite installation to test the material, structure, form, and the fabrication process. Priority was given for the development of a sustainable material along with the appropriate fabrication technique. Two changes were made:

1) a higher proportion of sand and oyster shells was used to increase the natural materials. The ratio was 1-part cement, 1-part sand, 2-parts crushed oyster shell, 1-part vermiculite;
2) the oyster shell particles were scaled up to 10 × 10 mm to increase the texture of the material to facilitate anchor points for different marine species.

Cement was tested as a binder to which different materials were subtracted and added. Subtracted materials included crushed rock from traditional concrete mixes. Additive substitute materials included vermiculite as aggregate and texture variation, iron oxide as colourant for the concrete, and locally sourced waste biomaterials as crushed oyster shells. Crushed discarded oyster shells were sourced from Sydney Fish Market. Including oyster shells into the mix encourages oyster colonisation onto structures (Figure 8). Oyster shell disposal relies on taking the shells to landfill. By using them in the build material, the project reduces landfill.

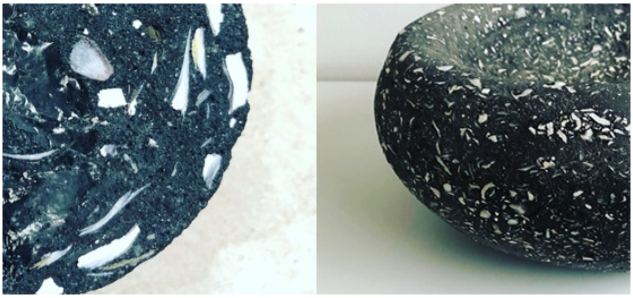


Fig. 8:
Composites made of concrete and crushed oyster shells for the large-scale prototype

Other projects are incorporating oyster shells in building materials and marine structures include tabby cement, a vernacular building technique from the southern US imported from Spain in the 17th Century (SHEEHAN & SICKELS-TAVES 2002), and artificial reefs such as the U.S. Fish and Wildlife Service Project PORTS (BRENNER 2015), the shellfish restoration project in Port Phillip Bay Australia (Victorian Fisheries Authority), the artificial oyster reef in Moreton Bay in Queensland, Australia, and the San Francisco Bay Oyster Restoration Plan (GEORGE 2005). However, none of these precedents use the oyster shells as a component in a 3D print material. The 3D print fabrication process is particularly important to achieve the complex geometries required for the site. The precedents being discussed use fabrication processes such as placing oyster shells in coconut fiber bags at the reef at Moreton Bay, whole oyster shells in plastic nets at the U.S. Fish and Wildlife Service Project PORTS, and whole oyster shells mixed with granite at the Port Phillip Bay project. For this project's location requirements, the Sydney fish markets are on Blackwattle bay, a tidal area with high marine traffic, very depleted native marine species, and in a densely urbanised part of the city with considerable tourism. In response to its versatile character, the Bio-Shelters ought to offer structural solutions combined with a functional means of rehabilitating the water so that they are highly visible at both high and low tide.

4.2 Large-Scale Prototypes

Next, the study sought fabrication options. Several prototypes were produced to refine on-site performance and material/design integration. The script was adjusted to give appropriate structural thickness at different sizes (Figure 9). A 1:5 prototype 120 × 80 cm was fabricated and installed on a box assimilating a flat seawall (Figure 10). Areas with different typological features correspond to varying information about sun exposure, tide, and site's material and physical topography as macro-inputs. To include them adds biodiversity, since the occurring zones attract different species according to their needs as meso-constraints. Additionally, the scheme suggests ways for tiling, connecting and mounting the model onto its intended site.

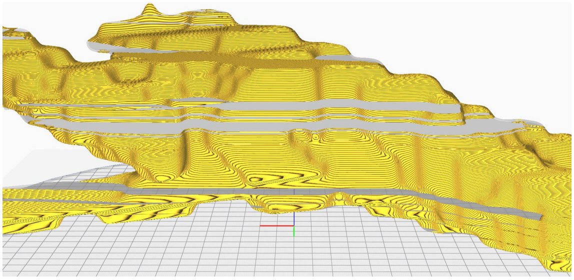


Fig. 9:
3D printing attempts testing material thickness

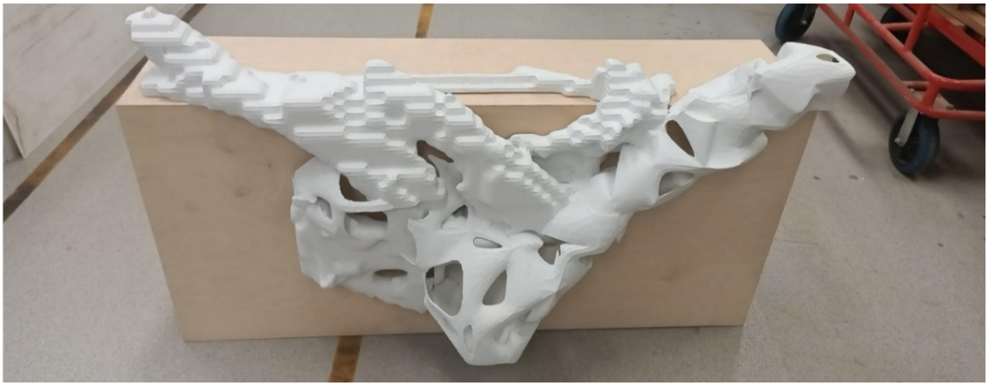


Fig. 10: PLA 1:5 model 120 × 80 cm in blocks, glued and placed on an approximated seawall

A segment was further enlarged to test additive and subtractive methods as fabrication options. A series of physical models were developed in ceramics using a potterbot 3D printer and then fired in a kiln. However, the scale of the project prohibits large scale kiln firing and even more it defeats its sustainable objectives. So, it was decided to combine Free Form Fabrication and CNC routing of formwork in tooling wax. FFF/FDM printing is relatively easy to adjust for different purposes as many of the mechanisms can be easily adjusted. This process can also be scaled up by introducing large gantry frames and robotic arms for delivering materials. CNC milling is suitable to give refined resolution to roughly printed wax mould pieces then used to cast the prototype model parts of the concrete/oyster shell composite. The wax is recyclable since it is melted and reused. The research group linked with Laing O'Rourke and their FreeFab™ technology using wax 3D printing and 5-axis CNC milling to produce a complex geometry via a commercial fabrication process (Figure 11). The specialists confirmed that this technology is able to fabricate the design. In the meantime, the research team fabricated a concrete mould with its own assets. A blue foam mould was created with 3-axis CNC milling, then the concrete mixture was poured to produce the prototype (Figure 12), which will be placed on-site and tested with regards to the initial aims.

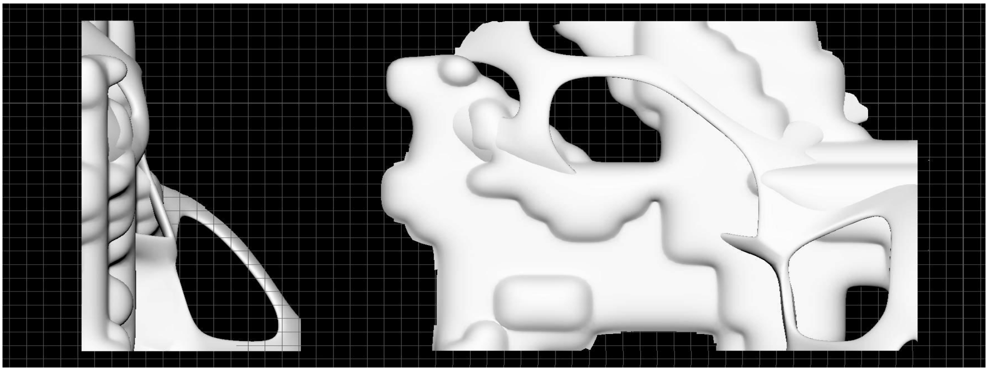


Fig. 11: Part of the model (front & side view) sent for physical scale prototyping with concrete/oyster shell composite by combining 3D printing and CNC wax moulding

Fig. 12: CNC fabricated mould and concrete prototype to be placed into water for testing

5 Completion of Research and Next Steps

The Bio-Shelters project employs computation to data-driven design, as a robust application from start to end. The problem is analysed to variables defined by their properties to interact and to produce results. The study extends what would commonly be an architectural approach into meaningful challenges for the scientific discourse. It investigates the suitability of computing to cross-disciplinary design for the environment, artificial and/or natural combined. It focuses on ecological data about reef colonies, and processes of formation by interacting with the site. The results evince remarkable complexity, adaptation and sophistication in shape, structure, materiality, and fabrication, suggesting an integrated design vision.

The future goals are set following the project's recent completion. The fabricated 1:1 prototype concrete/oyster-shell composite segment will be placed into the harbour to assess performance and to collect evidence that accounts for its operative efficiency. The 1:5 3-D printed PLA model will assist to communicate the project. Additionally, the Fishmarket development team will mention Bio-Shelters as a component into the tender documents to assure that it is included in the final scheme. The Bio-Shelters group will work with project architects and engineers to decide a specific location to run the script and to integrate its outputs into the greater landscape. A 1:1 prototype will be developed for that spot and be placed into the water for a longer time period. Alternative casting procedures will be tested, as the group will further engage with manufacturing partners to discuss commercial fabrication. With these steps, design thinking will further align with current technological advancements in computation as meanwhile, architecture's significance as a pioneering area of multidisciplinary and collaborative action will expand into the broader intellectual framing.

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