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Opportunities for further development of 3D-printed floating artificial reefs

Abstract

This article sets out the potential benefits of combining floating structures with 3D-printed artificial reefs to increase sustainable development of artificial reefs. Traditional artificial reefs are often sited on the seabed (bottom-founded) and are limited to a narrow range of suitable deployment sites. By utilising floating structure technology to create floating artificial reefs, these ecological installations leverage the advantages of floating structures to create more conducive conditions for improved bio-diversity, aquacultural harvests, and coral growth. These advantages include the ability to sensitively deploy floating reefs in the photic zone of deeper waters or where there are soft seabed conditions, speed and flexibility in deployment, creative use of mooring systems to reduce the impact of climatic and navigational threats, and the use of reefs to reduce the impact of coastal erosion and increased urbanisation. This article then considers how floating artificial reefs offer biological and environmental advantages, with the potential to deploy these reefs under environmental offset policies. Importantly, the article considers how 3D-printing technology can produce topographical optimisation of the floating structure, and potentially increase the speed of coral coverage, diversity of fish species and reduced settlement predation. It concludes with identifying future research opportunities to realise the delivery of 3D-printed artificial reefs as part of floating offshore development projects or for environmental offset programs.

Keywords: artificial reefs, floating structures, additive manufacturing, 3D printing, aquaculture, coastal infrastructure, environmental offset

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Brydon Wang,[1,2] Ding Wen Bao,[3,5] Selina Ward,[4] Dan Luo[1]

[1]School of Architecture, University of Queensland, Australia
[2]TC Beirne School of Law, University of Queensland, Australia
[3]School of Architecture and Urban Design, RMIT University, Australia
[4]School of Biological Sciences, University of Queensland, Australia
[5]Centre for Innovative Structures and Materials, School of Engineering, RMIT University Australia

Correspondence: Dan Luo, School of Architecture, University of Queensland, Brisbane, Queensland, Australia,
Email d.luo@uq.edu.au

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Introduction

The global socio-economic benefits of coral reefs have been estimated at USD 375 billion annually.[1] However, coral reefs are anticipated to decline globally by 70% by the middle of the 21st century due to rapid ocean warming.[2-4] To counteract this decline and to introduce coral reefs to more suitable environments, there has been a sustained effort, particularly since the 1950's,[5] to create artificial reefs to increase marine biodiversity and density in targeted undersea environments to enhance commercial fisheries.[6-8] These improvements include 'increasing the harvest of algae [and seaweed], lobster, other shellfish, and fishes',[5] reversing the existing decline in coral cover, serving to protect vulnerable coastlines from damaging wave forces.

The structural elements that have been used to construct these artificial reefs range across a wide spectrum: from sunken objects like train carriages, tanks, decommissioned ships, discarded vehicular tires, bridge rubble (i.e. 'materials of opportunity'.[6]) or repetitive use of concrete blocks or PVC pipes. However, research into the structural qualities of artificial reefs has turned to purpose-built modular design and arrangement features to enhance marine livestock diversity and habitat-enhancement for desirable species.[9,10] The structural forms of these artificial reefs take shape from the different desired objectives of the project, whether it may be for coral spawning, diversity and production of marine products, kelp assemblages, or where these reefs are introduced to mitigate habitat loss.[11] Within the field of reef design for fishery improvement, artificial reefs take on two primary purposes: first, those that are oriented to the recruitment of adult fishes, as seen from the first artificial reefs constructed in the US during the mid-19th Century and the approach to artificial reef deployment in Australia; or second, those that are oriented to enhancing the improvement of 'spawning, recruitment, and survival of earlier life history stages', as seen in Japanese artificial reef construction over the past centuries.[5,12,13] These divergent objectives produce artificial reefs of different materials and structural forms.[5] Other research has focused on the hydrodynamic characteristics of the artificial reef structure to 'provide a structure with low flow resistance, which will be a more suitable shelter for fishes and marine organisms'.[14] The authors posit that this need to create highly-specialised artificial reef forms suggests that the design and construction of artificial reefs is developing towards a responsive highly-customisable design and construction process to address local environmental conditions, such as 3D printing technology.

Most artificial reefs are sited on the seabed (bottom-founded) and must be located in shallower ocean environments. This places the artificial reef close to threats such as coastal development and pollutants (such as agricultural run-off and sedimentation). For example, the Great Barrier Reef ecosystems are vulnerable to phosphorus and nitrogen in fertiliser run-offs, which can lead to increased algae production and increased incidences of crown-of-thorn outbreaks that damage coral reefs.[15] Seagrasses can also be affected by sedimentation from soil erosion due to land-clearing upstream, which affects the turbidity of undersea environment and reduce sunlight penetration.[15] However, the phenomenon of reefs developing on offshore structures—most notably reefs on oil rigs—has seen an emerging focus on the potential for floating artificial reefs in the upper photic zone (depths ≤ 40m) to support more environmentally-sustainable offshore development. This has resulted in an emerging consciousness around repurposing decommissioned oil rigs into marine environments.[16,17] Between 1980s and 2018, more than 532 offshore platforms have been repurposed as artificial reefs in the Gulf of Mexico (accounting for just over a tenth of decommissioned platforms).[16]

At present, there have been limited purpose-built floating artificial reefs, such as artificial reefs as floating sculptures[18] or as part of floating vessels or habitats.[19] However, the authors' opinion is that when combined with modular very large floating structures (VLFS), artificial reef components that are attached to or in-built into these structures will leverage the technical advantages of floating structures, leveraging the ecological benefits that have been observed with novel ecosystems developed around offshore platforms.[20] At the same time, purpose-built modular floating artificial reefs could be specified as part of the technical brief and structure of offshore infrastructure projects, improving the overall environmental sustainability of the built structure. Such deployments of floating artificial reefs could potentially serve as offset sites to support 'no net loss' of biodiversity[21] under environmental offset policies used globally.[22] We set out the advantages of a floating artificial reef in the next section.

Advantages of floating artificial reefs

Floating modular artificial reefs structure offer numerous advantages:

I. Floating artificial reefs do not disrupt soft seabed floor environments and pose little impact to marine life within this stratum. Where accompanied by sensitive cut-outs to permit greater light penetration, there is no destruction of the existing marine environment below the footprint of the structure, unlike bottom-founded artificial reefs.[23,24]

II. Within certain biological parameters, the artificial reef structure would be suitable for deeper water or soft seabed conditions as the artificial reef could be floated and suspended 5 to 25 m below the ocean surface, allowing the reef to be located in the photic zone of deeper ocean environments where there is less marine biomass and diversity. Rigs-to-reef programs have been found to enhance marine life, including the bacaccio rockfish (*Sebastes paucipinis*) in southern California and cowcod (*Sebastes levis*).[25,26] A study of reefs on oil rigs demonstrated that decommissioned oil rigs deployed at depths greater than 500m could potentially offer suitable artificial reef habitats in the photic zone of the deep sea, particularly when 'epifaunal (encrusting) communities develop'.[27]

III. Flexibility in deployment – artificial reef modules could potentially be attached to offshore infrastructure and towed out and reconfigured – however, for these more flexible applications of floating artificial reefs, the structural design would need to be less customisable. The advantage offered is not just habitat enhancement for multiple aquacultural applications for a diverse range of marine livestock and seaweed farming, but also to propagate and seed new coral environments. Such artificial reefs could also be strategically placed to recruit and retain larvae 'that would otherwise be "lost" to inhospitable substrates'.[28]

IV. The mooring system for the floating structure also provides some unique advantages. First, the buoyancy of the floating structure and be adjusted to respond to impending above sea threats such as cyclones or heatwaves. By temporarily lowering the floating artificial reef by up to 5m below the ocean surface in response to these threats, there is an ability for the reef to be made less vulnerable to cyclone damage and bleaching events during a heat wave. Where required, mooring systems can also be lowered to avoid marine vessel traffic and the threat of collision. Finally, the adoption of a taut mooring line system can also be designed to generate electricity through wave energy converters attached to the mooring lines.[29] With this power supply, there is further potential for these artificial reefs to be equipped with pump-and-sprinkler systems to sprinkle seawater and break the ocean surface to reduce light penetration, cool the reef and further reduce bleaching events

V. Increased pace of maturity to allow these modules to be rapidly constructed to create new marine habitats and be customised for oyster farming, sea cucumber farming, lobster farming, increasing biomass of specific fish species, or new coral reefs. Individual artificial reef modules can be seeded with coral or other marine life prior to assembly. Surfaces of the artificial reef will be prepared to maximise coral and other invertebrate settlement with the use of settlement inducers and crustose coralline algae. This would increase deployment rate and improve overall construction periods for the artificial reef. For example, to expedite this process of starting the growth of an artificial reef, the authors suggest that there could be a collection of collect coral larvae at spawning time, which would then be allowed to settle on small settlement tiles covered with crustose coralline algae and suitable bacterial films. Once these coral recruits reach a suitable growth stage – when they have acquired their *Symbiodiniacaea* (the symbiotic microalgae that live within the coral cells and supply most of their carbon) and have calcified to the appropriate level, these small tiles could be attached to the artificial reef. A number of different species of coral larvae could also be raised including brooding species that settle and grow quickly and would form an important part of the artificial reef fauna. Small quantities of adult tissue could also be grafted onto substrates and attached to the artificial reef as well as a way of accelerating coral growth.

VI. Floating artificial reefs may also assist in reducing coastal erosion that is impacting economic activity and property values along coastlines, shading and cooling waters to reduce the effect of warmer waters on wet weather events on our coastlines. These reefs could be deployed as a floating or submerged breakwaters to protect sensitive coastlines and nearshore facilities.[30]

Biological and Environmental advantages of artificial reefs

Artificial reefs serve to increase biomass of a particular species of marine life where the specific regional population is limited by suitable habitat (i.e. available resources). In these scenarios, the availability of an artificial reef serves to decrease predation risk, allow for increased food availability and better opportunities for reproduction. Where the regional population limitations arise from recruitment with fluctuations in population numbers due to 'survival, dispersion and settlement of larvae', artificial reefs might have limited effect on increasing biomass.[31]

The marine life population of various species can vary over time on the artificial reef—one species may dominate for a season, or a 'successional pattern can occur' across time. However, 'equilibrium community structure' generally occurs within half a decade.[32] Artificial reefs oriented on specific aquacultural outcomes can also be seeded with the specific species desired: clams, abalone, oysters, sea urchins and new coral reefs.[32]

Offshore platforms repurposed as artificial reefs have seen increased fish biomass within a radius of a 300m radius.[32,16] The authors anticipate that the deployment of artificial reefs with highly-customisable void spaces that support a spectrum of complexity of structural modification will produce more conducive environments for coral reef fish larvae and increase the recruitment of juvenile fish.[33] Similarly, the potential to customise structural modifications allow these artificial reefs to serve as specialised habitats for a wider range of fish stocks and marine products, such as for lobster farming and seaweed farming, potentially unlocking the co-location of multiple marine industries, increasing marine livestock and diversity, improve

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commercial and recreational catch rates. Customisable artificial reef modules can also provide visual interest to provide reef attractions for divers, expanding eco-tourism possibilities.[34]

Offshore platforms repurposed as artificial reefs have been suggested as means of discouraging illegal trawl fishing, particularly in flat-bottom areas such as the north-west shelf of Australia, sections of the North Sea and the Adriatic Sea. This offers a potential significant advantage where floating artificial reefs could be deployed to protect benthic habitats.[16] These offshore platforms have also been observed to play a key ecological role in serving as a 'refuge for… megafauna such as seals and whales'.[35]

Floating artificial reefs could also potentially be deployed to serve as sites for environmental offsets in the marine environment (for example, under the *Environmental Protection and Biodiversity Conservation Act 1999* (Cth) in Australia). While environmental offset mechanisms are not without controversy or criticism on ecological, legal and political grounds, the global use of offsets stems from a desire for net neutral or positive impact on the marine environment based on allowing conservation efforts undertaken by a developer to compensate for environmental harm caused in a different location.[15] In scenarios where floating artificial reefs are a required component of offshore developmental approvals, there is potential to address the phenomenon of coastal hardening—where natural marine habitats are replaced with man-made structures—and shift some of the complexities and costs associated with preservation and rehabilitation of coastal habitats (such as seagrass) onto offshore developers. In other jurisdiction-specific offset policies (such as Australia), developers can potentially outsource offsets to the government (or third party) to carry out environmental offset activities, allowing the government to potentially take on board the deployment of floating artificial reefs.

However, ocean governance of offshore development is complex and involves multiple regulatory stakeholders tasked with environmental protection. In Australia, the installation of a floating artificial reef would involve discussions with, and potentially obtaining approvals from, federal, state, and in some cases, local government agencies. For example, the installation of a floating artificial reef in Queensland, Australia varies depending on the exact site of deployment, potentially requiring Tidal Works development approval, a Marine Park permit, engagement with the *Sea Installations Act 1987* (Cth) and the *Environment Protection and Sea Dumping Act 1982* (Cth) (and potential Commonwealth sea dumping permit). Further, in situations where the approval of an offset for an offshore development could result in a financial benefit to government entity tasked with carrying out offset activities, including the deployment of floating artificial reefs, vigilance will be required against the threat of regulatory capture.[15] It is imperative that environmental offset mechanisms are intended to be used as a last resort, after options to avoid or minimise environmental harm have been explored and ruled out.

Potential artificial reef project

The authors propose a highly-customisable floating artificial reef comprised of 3D-printed modules attached to floating pontoons that are submerged 2 to 25m deep to avoid strong surface waves. These modules can be rapidly constructed to create new marine habitats and be customised for a range of ecological and commercial purposes, including: oyster farming, sea cucumber farming, lobster farming, increasing biomass of specific fish species, or new coral reefs. For example, these marine habitats could be used as oyster farms, providing not just commercial benefits through aquaculture, but also the inherent benefit of improved water quality through the natural filtration provided by oysters (for example, *Saccostrea commercialis*).[36]

By adopting a hybrid system comprising modular floating structures and 3D-printed modules, the artificial reef could be floated and suspended 5 to 25m below the ocean surface, allowing the reef to be located in sterile, deeper ocean environments (offshore ocean space) to create marine habitats ideal for aquaculture, and alive with corals and fish. A novel taut mooring line system will be designed to generate electricity by using wave energy converters and to allow the buoyancy of the artificial reef to be adjusted in response to cyclones or heatwaves.

In terms of the proposed structural design of the floating reef, the authors suggest the deployment of generative design and structural topology optimisation. The application of generative design and topology optimization methods instead of traditional ways of designing artificial reefs is crucial to customizing reef habitat. This innovating structural design method will yield crevices and voids to allow higher surface-area-to-volume ratios and increase the speed of coral coverage, diversity of fish species, biomass, juvenile attraction and reduce post-settlement predation.[1,6,37] Simultaneously, such a structural design approach provides an additional ability to seamlessly design innovatively-shaped artificial reefs for attracting divers to boost the local tourism industry.

The optimal shape of the artificial reef under the wave and current actions will be determined by using topology optimisation techniques. The optimisation constraints include satisfying the strength, stiffness, stability and durability criteria to ensure the printed reef has adequate strength to withstand wave actions, storms/typhoons and other hydrodynamic/combined actions. The reef will also feature surface textures and contours to provide a conducive environment for coral and algae growth and internal spaces for sea creatures to hide and build their homes. Generative design or topology optimization enables the production of free-form and porous structure components that are highly customizable and material efficient to suit a range of economic and environmental outcomes.

Building on the previous research on "Environmental data-driven performance-based topology optimisation for morphology evolution of artificial Taihu stone"[38] and "Human-made corals for marine habitats: Design optimization and additive manufacturing",[39] the authors suggest a hybrid generative design method that integrates the *Computational Fluid Dynamics* (CFD) and *Bi-directional Evolutionary Structural Optimization* (BESO) techniques to predict and optimise the performance of coral reef and environment in the early stage of the design.[40] CFD simulation enables engineers to predict and optimise the performance of buildings and environment in the early stage of the design and topology optimisation techniques. BESO is a finite element-based topology optimisation method, that has been widely used in structural design to evolve a structure from the full design domain towards an optimum by gradually removing inefficient material and adding material simultaneously. For example, an artificial reef can be generated based on the environmental data-driven performance feedback using the hybrid generative design method to increase the variety of reef's porous and intricate form to support aquaculture, commercial fishing activities, and seaweed farming to be co-located in different sections of the artificial reef structure.

To allow such structural design to be as customisable as possible, the authors also propose the use of 3D printing technology. Printing material for the artificial reefs would be biologically friendly to coral and marine-friendly, ensuring that its pH is similar to that of seawater and that any leaching that occurs stays within acceptable limits. The printed reef provides a suitable substrate and good recruitment surface for coral attachment and growth.

Owing to the water buoyancy and preference of irregular surfaces for attachment of marine organism, 3D printed structures have great potential for fabricating submerged structures compared with 3D printing systems deployed onshore. First, printing submerged structures allows the buoyancy force in the water body to reduce the self-weight of the overlaying layers, reducing deformation of material as successive layers are added,[41] and improving its ability to create structural overhangs. This allows the rapid printing of structures with additional geometrical complexity without increasing the cost of production. Second, as these underwater structures fulfil an environmental or aquacultural requirements, they do not need to meet onerous industry standards or comply with building codes, permitting the use of coarser-grained aggregates, which reduce the need for cement and result in less shrinkage. This again provides a significant advantage compared with traditional 3D printing given the increase in construction speed and efficiency.[42] Third, water flow will naturally wash away loose particles over time, reducing the post-processing workload for particle-based prints. Finally, 3D printing systems potentially offer rapid large-scale low-cost printing which can be based on cement or bio glue in sensitive habitat, where local materials can be used. Other ingredients such as glass-fibre reinforced polymers and slow-releasing reef nutrients, bacterial cultures, or extracts of crustose coralline algae can potentially be added to the base aggregates of 3D printing to facilitate the growth of the reef; thereby increasing the aquaculture benefits of the artificial reef.[43]

The authors note that 3D printing is currently used in limited ways in the construction of artificial reefs. The current large scale 3D printing approaches use 3D printing techniques such as *Fused Deposition Modeling* (FDM) or *Powder Bed Fusion*. However, these techniques are primarily developed for building construction, which has significant limitations such as costly customized printing materials,[44] sub-optimal structural performance with mixed isotropic and anisotropic properties,[45] and low printing resolution with rough surface finishing that reduces complex voids crucial for providing conducive environments for a wide spectrum of marine life.[6] However, printing for submerged structure brings unique opportunities for additive manufacturing. Being submerged in water, buoyancy provide additional support for printed objects that facilitates the aggregate of materials. Also adopting local materials such as reef debris would increase the entanglement within the aggregate, thus allowing additional geometrical flexibility for the printed structure with potentially increasing ability to print cantilevers and overhangs. With increasing geometrical flexibility, and the possibilities of wash-away-able temporary support, structures with complex cavities at different scales can be printed for marine habitat with complex ecosystems such as artificial reef. Also, adopting local coarse debris not only minimize the impact to local environment, but also generates perforation and cavities withing the aggregate itself, provide ideal surface quality for the growth of micro-organism and attachment of coral. Incorporating modern workflow of digital design and advance manufacture, it's possible to design and print customizable structure optimized either as a stand-alone deployable base for artificial reef, or as an integrated part of floating structure that bears the dual purpose of fostering designated habitat. (Figure 1).

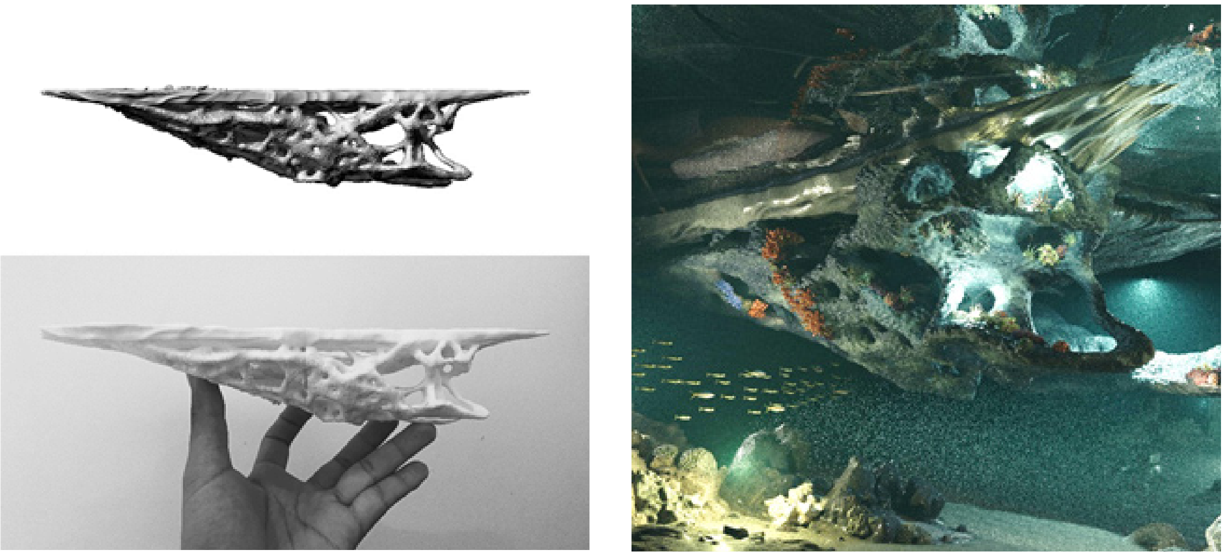

Figure 1 Floating artificial reefs –digital model, 3d printing model and rendering from RMIT Master Studio CORAL.

Concluding remarks

With increasing offshore floating developments and advances in floating structures technology, there is an opportunity to create floating artificial reefs that allow the creation of new marine environments within the 5 to 25 m depth in deeper offshore waters that typically have little marine biomass and diversity. Such a project builds on existing research that demonstrates the use of oil rigs (and other floating structures) as artificial reefs in offshore environments produces higher biomass and diversity. Wave energy can be harvested by installing Power Take-Off systems in between segments of taut mooring line system as for the heaving wave energy converter.

There is a wider application of such floating artificial reef technologies beyond offshore development, including nearshore and wetland environments. For example, these same floating components can also be customised for purposes beyond artificial reefs, including for use as floating garden spaces on wetlands. For example, such modules can be used to grow native Australian plants (*Phragmites australis*, *Baumea articulata*, and *Juncus kraussii*) in wetlands that can detox PFAS-contaminated water.[46,47]

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Artificial reefs have the potential to be included in project briefs for future floating developments to ensure that these projects meet potential technical and regulatory requirements. It is anticipated that the inclusion of artificial reefs with offshore developmental approvals will allow superior sustainability outcomes for projects as diverse as floating breakwaters and floating windfarms.

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Conflict of interest

Author declares there are no conflicts of interests.

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