Topology-Optimized 3D-Printed Marine Structures for Enhancing Habitat Complexity and Biodiversity in Coastal Waters

Bartolomeo Ludovisi
School of Computing, Clemson University, Clemson, SC, USA.
bartolomeo.ludovisi@clemson.edu

Venancio Mazzanti
Department of Computer Science, University of Central Florida, Orlando, FL, USA.
mazzantivenancio@ucf.edu

Vilhelm Kristiansson
Department of Computer Science, Colorado State University, Fort Collins, CO, USA.
vilhelm488@colostate.edu

Abstract

Coastal marine habitats are increasingly modified by shoreline hardening, restoration structures, and artificial reefs whose surfaces often provide limited topographic and interstitial complexity. Biodiversity gains from such structures depend not only on material or placement but also on the geometric organization of voids, surfaces, overhangs, and connecting channels. This manuscript develops a methodological framework that couples topology optimization with habitat-complexity metrics for the design of 3D-printed marine structures. The framework treats a structure as a density field subject to structural equilibrium, volume, manufacturability, and hydrodynamic constraints, while augmenting the objective with a complexity index that combines fractal dimension, void fraction, pore-size heterogeneity, and curvature density. A saturating biodiversity-response function is introduced as a design hypothesis for trading complexity against structural and ecological uncertainty rather than as a fitted empirical model. The analysis shows that unconstrained complexity maximization can reduce stiffness, increase drag, and create narrow dead-end voids with poor exchange, so the useful design problem is not maximizing geometric irregularity but placing complexity where it improves effective habitat volume without compromising load paths. The paper also specifies how adaptive monitoring can be integrated into design evaluation, including the practical constraints of environmental sensing. The contribution is a technically explicit design logic for reproducible, ecologically informed topology optimization of printed marine structures, with implications for restoration practice and for the evaluation of habitat complexity as a design variable.

Keywords

topology optimization; habitat complexity; 3D printing; eco-engineering; marine biodiversity; coastal restoration

1. Introduction

Coastal marine ecosystems are exposed to cumulative pressures from shoreline development, dredging, pollution, fisheries, and climate-related changes in temperature, sea

level, and storm intensity [1]. Responses to these pressures frequently involve hard structures such as breakwaters, seawalls, revetments, and artificial reefs. Such structures can protect infrastructure or restore substrate, but their ecological value is not automatic. Smooth, homogeneous surfaces tend to support simplified assemblages, whereas surfaces with crevices, pits, ledges, and overhangs can alter settlement, predator-prey interactions, and refuge availability. The ecological role of structural complexity is well established in benthic and reef systems, where topographic heterogeneity influences recruitment, survival, and species coexistence [2]. Complexity is nevertheless multidimensional: it includes surface roughness, fractal scaling, void architecture, pore-size distribution, and the density of edges and curvature transitions [3]. A design method that targets only one of these dimensions may increase visual irregularity without producing usable habitat.

Eco-engineering has emerged as a practical route for modifying coastal infrastructure to deliver ecological benefits alongside engineering functions [4]. Artificial reefs and restoration substrates have been used for decades to restore hard-bottom habitat, enhance fish production, and compensate for lost structural complexity [5]. Yet many artificial structures remain standardized, and their ecological performance varies with material, orientation, depth, hydrodynamic exposure, and the scale at which complexity is expressed. Topology optimization offers a computational alternative: rather than selecting a fixed lattice or sculpted tile, it distributes material within a design domain according to a stated objective and constraints [6]. Additive manufacturing can then realize geometries that are difficult to produce by casting or assembly, including graded porosity, internal channels, and spatially varying surface texture [7]. The combination is technically promising because it allows habitat features to be treated as design variables rather than post hoc additions.

The central problem addressed here is that ecological complexity and structural performance are usually optimized in separate languages. Ecological studies describe complexity through metrics such as fractal dimension, rugosity, and interstitial volume, while engineering design describes performance through stress, stiffness, fatigue, drag, and manufacturability. These descriptions are not directly commensurable. A design can be ecologically rich in a metric sense yet structurally inefficient or hydrodynamically penalizing; conversely, a strong, low-drag structure may offer little effective refuge. Ecosystem-based coastal defence also requires that ecological benefits not be treated as decorative additions to a load-bearing system [8]. The contribution of this paper is therefore a coupled formulation in which topology optimization is constrained by engineering requirements and evaluated through a habitat-complexity index and a bounded biodiversity-response hypothesis. The aim is not to report field performance but to make explicit how complexity can be represented, constrained, and traded against structural and hydrodynamic consequences in printed marine structures.

2. Ecological and Engineering Design Problem

Artificial marine structures differ ecologically from natural rocky or biogenic habitats in several respects. They often lack the long-term weathering, biogenic accretion, and heterogeneous material interfaces that produce diverse microhabitats. Urban marine infrastructure can be designed to be multifunctional, but ecological outcomes depend on the surrounding seascape and on the scale of intervention [9]. Experimental work on intertidal structures has shown that structural complexity and component type can increase biodiversity independently of total area, indicating that geometry and material arrangement are not simple proxies for surface area [10]. This finding matters for topology optimization because adding

surface area is easy, whereas adding effective habitat volume is constrained by exchange, light, sedimentation, and structural continuity.

Engineering constraints further narrow the design space. Coastal defence structures must resist wave loading, buoyancy, scour, and impact, and their geometry is constrained by construction, maintenance, and safety requirements [11]. Ecological engineering can serve coastal protection, but the ecological and engineering objectives must be aligned at the stage of concept design rather than reconciled after structural form is fixed [12]. Topology optimization provides a formal way to explore that alignment. Density-based methods can handle complex domains and multiple constraints, although they require regularization to avoid mesh dependence and to produce manufacturable boundaries [13]. For marine applications, the optimization must also account for the ecological legacy of hard coastal defence structures, which can alter sedimentation, flow, and community composition [14]. Biodiversity management in coastal systems is ultimately linked to ecosystem services and to the spatial arrangement of habitats, not merely to local surface treatment [15].

The design problem is therefore stated as follows: within a bounded structural volume and under specified hydrodynamic and mechanical loads, distribute solid material and void space so that a measure of habitat complexity is increased, structural compliance and drag remain acceptable, and the resulting geometry can be additively manufactured and deployed. This problem is multi-objective and non-unique. Different Pareto-optimal structures may be appropriate for wave-exposed breakwater units, low-energy restoration reefs, or estuarine habitat modules. The framework developed below is intended to make those choices explicit through metrics, constraints, and sensitivity analysis.

3. Methodological Framework

3.1 Habitat-complexity metrics and ecological objectives

The framework begins by defining a scalar complexity index over the structural domain. The index is not intended to replace ecological field assessment; it is a design-stage summary of geometric features that have plausible ecological relevance. Four normalized components are combined: fractal dimension, void fraction, pore-size heterogeneity, and curvature density. Fractal dimension captures scale-dependent surface irregularity; void fraction represents the proportion of interior or interstitial space available for occupation; pore-size heterogeneity describes the spread of accessible void diameters; and curvature density represents the frequency of edges, ridges, and concave transitions that can provide refuge or settlement cues. The proposed index is

$$H = w1Df + w2Vv + w3Pp + w4Kc$$

where H is the habitat-complexity index, Df is the normalized fractal dimension, Vv is the void fraction, Pp is the normalized pore-size heterogeneity, Kc is the normalized curvature density, and w1 to w4 are nonnegative weights summing to one. The weights are design assumptions that must be specified before optimization because they encode the target community or life-history stage. For example, a design intended for juvenile fish refuge may weight void fraction and pore-size heterogeneity more heavily than curvature density, whereas a design for sessile invertebrate settlement may emphasize curvature and fractal dimension. The index is bounded by construction if each component is normalized to the interval from zero to one and the weights sum to one.

The use of H as an objective term requires care. A high H can be produced by many small disconnected voids, which may have little effective habitat value because exchange is limited. The framework therefore does not optimize H alone. It pairs H with an effective-volume correction and with transport constraints discussed below. Complexity is treated as a spatial allocation problem: the question is where to place voids, overhangs, and channels so that they remain connected to the external flow and accessible to organisms. This interpretation is consistent with evidence that complexity effects depend on the type and arrangement of structural elements, not only on their quantity [10].

3.2 Topology optimization formulation

The structural domain is discretized into finite elements, and each element is assigned a density variable between zero and one. The optimization seeks a material distribution that balances structural performance, material use, and habitat complexity. A representative objective is

$$J(\rho) = wsCs(\rho) + whCh(\rho) - wbH(\rho)$$

where ρ is the density field, Cs is structural compliance, Ch is a material or manufacturing cost term, H is the habitat-complexity index from the previous section, and ws, wh, and wb are nonnegative weighting coefficients. The negative sign on H expresses the desire to increase complexity, while the positive terms penalize deformation and material use. The objective is minimized subject to equilibrium, volume fraction, and bound constraints. The equilibrium relationship for linear elastic behavior is

$$K(\rho)u = f, E(\rho) = Emin + \rho\text{^}p(Es - Emin)$$

where K is the global stiffness matrix, u is the displacement vector, f is the external load vector, E is the interpolated Young modulus, Emin is a small residual stiffness used to avoid singularity, Es is the solid material modulus, and p is a penalization exponent greater than one. The interpolation is a standard density-based scheme; it is not a material model calibrated for a particular printed alloy or polymer. Material-specific calibration would be required before structural certification, but the formulation itself only requires monotonic stiffness interpolation and a feasible solid-void contrast.

To avoid mesh-dependent, unmanufacturable geometries, the density field is filtered before physical interpretation. A common distance filter is

$$\tilde{\rho}i = \sum j\, wij\, \rho j \,/\, \sum j\, wij, wij = max(0, rmin - dij)$$

where $\tilde{\rho}$i is the filtered density at element i, ρj is the unfiltered density at neighboring element j, wij is a distance weight, rmin is the filter radius, and dij is the distance between element centers. The filter imposes a minimum length scale, which is important for 3D printing because very thin struts and sharp re-entrant features may be unprintable or fragile. The filtered field is then projected toward zero or one through a smooth Heaviside-like projection, and the resulting isosurface is extracted for manufacturing. This step is essential for marine structures because surface discontinuities can concentrate stress and because narrow crevices may clog with sediment or be inaccessible to targeted organisms.

The optimization is non-convex and may converge to different local designs depending on initialization. That property is not merely a numerical nuisance; it reflects genuine design freedom. A lattice-like initialization tends to produce periodic struts, while a random or biologically inspired initialization may produce clustered voids and irregular channels. Continuation methods can reduce premature convergence, and multiple runs should be

retained as alternative design candidates rather than discarded. The appropriate selection among candidates depends on the intended deployment environment and on the ecological weights chosen for H.

3.3 Material, manufacturing, and marine boundary conditions

Additive manufacturing expands the feasible geometry but introduces its own constraints. Material extrusion, powder-bed fusion, and binder jetting differ in resolution, anisotropy, porosity, and post-processing requirements [7]. For marine deployment, the printed material must resist hydrolysis, salt crystallization, UV exposure, biofouling, and abrasion. A topology-optimized geometry that is admissible for a laboratory printer may not be admissible for a field-deployed unit if the minimum strut thickness, overhang angle, or internal channel diameter falls below process limits. The optimization should therefore include manufacturability constraints on minimum feature size, maximum overhang, and minimum drainage diameter. These constraints also have ecological consequences: a minimum channel diameter can prevent the optimizer from creating dead-end pores that would score highly on void fraction but remain poorly flushed.

Hydrodynamic loading is a primary boundary condition for coastal structures. A simplified drag estimate for a unit in a steady current is

$$FD = 0.5CD\rho wAsU^2$$

where FD is drag force, CD is the drag coefficient, ρw is seawater density, As is the projected area normal to flow, and U is current velocity. The drag coefficient depends on shape, Reynolds number, surface roughness, and biofouling, so the expression is an order-of-magnitude design constraint rather than a predictive field model. It shows why complexity cannot be increased without limit: added projections and internal surfaces can increase projected area and form drag, and they can also trap sediment or create low-exchange zones. In wave-exposed settings, oscillatory loading and vortex shedding require more detailed analysis than steady drag alone.

Mechanical constraints are imposed as inequalities on stress and deformation. A representative constraint set is

$$\sigma vm(x) \leq \sigma allow/\gamma m, \delta max \leq \delta lim$$

where σvm(x) is the von Mises stress at location x, σallow is the allowable stress for the printed material, γm is a material safety factor, δmax is the maximum displacement, and δlim is the serviceability limit. For marine structures, fatigue and biofouling-induced load changes may dominate over short-term static strength, so the safety factor should reflect the intended service life and inspection regime. The constraint set also ensures that the ecological objective does not create slender load paths that fail under storm loading or handling during deployment.

3.4 Monitoring and adaptive evaluation

Design-stage metrics cannot establish biodiversity outcomes. Field evaluation is required to determine whether printed complexity actually increases colonization, survival, or species richness. Sensor networks and Internet-of-Things approaches can provide environmental observations, but practical deployments face power, communication, interoperability, and maintenance challenges in coastal settings [16]. The monitoring design should therefore be sparse and targeted: pressure or velocity sensors at representative exposure levels, temperature and salinity loggers, and repeated photographic or settlement-plate sampling. The purpose is not to instrument every unit but to estimate whether the constructed complexity

produces the intended effective habitat volume and whether sedimentation or biofouling rapidly fills the designed voids.

Adaptive evaluation can feed back into the weights and constraints of the optimization. If voids fill with sediment within a season, the effective void fraction should be reduced relative to the nominal void fraction. If high-complexity units show no recruitment advantage, the assumed biodiversity-response function is not supported and should not be used to justify further complexity. This feedback logic is deliberately conservative: the optimization model proposes candidate geometries, while field evidence determines whether the ecological objective term is credible for the target site.

4. Analytical Assessment and Design Implications

4.1 Complexity-stability trade-offs

The coupled formulation reveals a structural reason why unconstrained complexity is not desirable. Each additional void or overhang changes the load path through the material field. In density-based topology optimization, the optimizer can satisfy stiffness constraints by thickening remaining members, but thickening consumes material and may close the very voids that were intended as habitat. If the complexity weight wb is increased without a volume or feature-size constraint, the optimizer may produce a highly irregular but mechanically marginal design. If the volume constraint is tightened, the optimizer may remove small features to preserve global stiffness. The resulting trade-off is not a defect of the method; it is the engineering content of ecological design.

The trade-off can be managed by separating load-bearing material from habitat-generating material. A primary structural frame can be optimized for stiffness and drag, while secondary surface modules are optimized for complexity under lower mechanical loads. This separation is consistent with the logic of eco-engineering interventions, which often modify surface form without altering the primary structural function [4]. It also reduces the risk that ecological scoring drives the entire load path into an inefficient configuration. The optimization can be formulated as a two-scale problem: a coarse density field defines the load-bearing skeleton, and a fine surface field defines voids, ridges, and channels within a prescribed thickness. The two fields are coupled through a volume constraint and through the drag and stress limits.

4.2 Scale, connectivity, and biodiversity response

Habitat complexity operates at multiple spatial scales. A crevice that shelters a small crustacean may be irrelevant to a fish, while a large overhang that shelters fish may offer little surface area for sessile invertebrates. The complexity index H can be computed at several filter scales, and the weights can be adjusted to represent the target assemblage. This scaling is important because printing resolution and structural member size impose a lower bound on achievable features. A design optimized for one scale may be unnecessarily complex, and therefore costly, at another.

For design evaluation, a bounded response function is useful as a normative hypothesis:

$$\Delta\frac{B}{B}0 = \lambda\frac{(H - H0)}{(1 + \theta|H - H0|)}$$

where ΔB/B0 is the proportional change in a biodiversity endpoint relative to a reference structure, H0 is the reference complexity, and λ and θ are positive shape parameters. The function is saturating: modest increases in complexity can produce gains, but further increases

yield diminishing returns. It is not an empirical law, and λ and θ must be estimated from site-specific data before the function is used predictively. Its value in the design framework is that it prevents the optimizer from treating complexity as an unbounded good. The same logic applies to connectivity. Oyster reef restoration has shown that substrate and reef architecture influence recruitment and community development, but outcomes depend on larval supply and hydrodynamic setting [18]. Coastal plant communities similarly alter flow, sedimentation, and habitat structure in ways that cannot be captured by a single local complexity score [19]. In tropical seascapes, mangrove and reef habitats can interact to influence fish biomass, indicating that connectivity among habitat units may matter as much as within-unit complexity [20].

4.3 Failure modes and uncertainty

Several failure modes are specific to printed marine structures. First, clogging by sediment and detritus can reduce effective void volume, especially in low-flow environments. Second, biofouling can smooth small-scale roughness and fill narrow crevices, changing both habitat value and drag. Third, mechanical fatigue at sharp re-entrant features can initiate cracks, particularly in anisotropic printed materials. Fourth, abrasive scour around the base can undermine the unit and alter its orientation. The optimization framework can reduce but not eliminate these risks. It can impose minimum channel diameters, rounded transitions, and drainage paths, and it can penalize features that are predicted to be hydraulically isolated. It cannot predict the stochastic settlement of larvae or the long-term accumulation of biogenic material.

Uncertainty in the ecological weights is another limitation. The weights w1 to w4 in H are value judgments about which habitat features matter for a given management objective. Different stakeholders may assign different weights, and the resulting Pareto front may contain designs that are ecologically defensible but structurally dissimilar. A rigorous workflow should therefore report the sensitivity of selected designs to weight perturbations and should not present a single optimized geometry as uniquely correct. The same caution applies to the response function in the previous subsection: it is a design aid, not a substitute for monitoring.

5. Discussion

The framework developed here treats habitat complexity as a design variable that is coupled to structural mechanics and manufacturing constraints. This differs from approaches that add surface texture to a fixed structural form or that evaluate ecological benefit only after deployment. By embedding complexity in the topology optimization objective and penalizing hydraulic isolation, the method can generate candidate geometries that are both structurally coherent and ecologically interpretable. The contribution is methodological rather than empirical: it specifies how to formulate the problem, which quantities must be defined before optimization, and where the model must be calibrated against field data.

A practical implication is that ecological objectives should be expressed through a small number of transparent metrics. The four-component index used here is not exhaustive, but it separates distinct geometric properties that can be diagnosed when a design fails. If a unit performs poorly because voids are too small, the pore-size term is implicated; if it fails because flow is blocked, the connectivity constraint is implicated. This diagnostic structure is more useful than a single uninterpretable complexity score. It also allows engineers and

ecologists to negotiate the weights explicitly rather than embedding assumptions in a fixed design.

The framework does not resolve the fundamental uncertainty of ecological prediction. Biodiversity responses to artificial structures depend on larval supply, predation, competition, and the surrounding seascape. A topology-optimized structure can only modify the local physical template. It cannot compensate for regional habitat loss or poor water quality. The appropriate use of the method is therefore within an adaptive management program that treats optimized designs as testable interventions, not as guaranteed biodiversity enhancements.

6. Conclusion

This paper has presented a coupled topology optimization and habitat-complexity framework for 3D-printed marine structures. The framework represents a structure as a density field subject to equilibrium, volume, manufacturability, and hydrodynamic constraints, and it augments the structural objective with a complexity index based on fractal dimension, void fraction, pore-size heterogeneity, and curvature density. A saturating biodiversity-response function is introduced as a design hypothesis, and the analysis identifies the principal trade-offs between complexity, stiffness, drag, and hydraulic exchange. The main conclusion is that useful ecological complexity is not equivalent to maximal geometric irregularity. Complexity is most valuable when it is connected to external flow, sized above clogging thresholds, and placed on structural elements that do not compromise load paths. The framework provides a technically explicit basis for generating and comparing printed marine structures, and it identifies the points at which field calibration and adaptive monitoring are required before ecological claims can be made.

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