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Diatom-inspired Computational Design of Radial Framework Structures: The Case of Asterolampra

Stephanie BACHIR*

*Alfred Wegener Institute for Polar and Marine Research
Bussestraße 27, 27570 Bremerhaven
stephanie.bachir@awi.de

Abstract

In this paper, an interdisciplinary geometry-based computational design method is proposed to generate and optimize a catalogue of radial framework structures inspired by the structural patterns of centric diatoms. Diatoms are unicellular microalgae forming the base of the marine food chain. With their high strength-to-weight ratios and over 100,000 species exhibiting visually striking designs, diatoms serve as exemplary models for lightweight structures that are both robust against various types of loading and exhibiting interesting "architectonic" features. A case study based on the iconic Asterolampra diatom is presented, where key morphological characteristics such as the "tuning fork structure" are identified and translated into parametric models developed within Rhino/Grasshopper environment. The study evaluates the structural behavior of different patterns and their variations as applied to a generic dome using Karamba 3D. The tuning fork concept is then employed in designing a shade structure resembling a funnel shape. The exploration of this method extends to a nonstandard, asymmetrical version of the same design. The structures are optimized using an evolutionary solver, Octopus, and the efficiency of this approach is compared for both designs. This interdisciplinary research aims to provide insights into the application of diatom-inspired designs in architectural practice, seeking to optimize structural efficiency while incorporating novel architectural features derived from nature.

Keywords: Interdisciplinary design, computational design, diatoms, lightweight structures, patterns, bio-inspired, radial structures, structural optimization

1. Diatoms

Diatoms are unicellular microalgae belonging to the group of phytoplankton, floating invisibly through the world's aquatic bodies. Through their photosynthetic activity, these primary producers contribute to around 20–25% of the Earth's oxygen [1]. Besides their crucial role in Earth's ecological balance, diatoms stand out as remarkable examples of natural structures being the only organisms on the planet with cell walls (called frustules) composed of transparent, intricately structured opaline silica, a unique variant of cell walls [1]. Not only do they provide a protective shield against predators, but these highly detailed frustules provide additional functions such as nutrient filtration as well as light and buoyancy control. The frustule consists of two overlapping valves (epitheca and hypotheca) that fit together like a petri dish and the copulae, or girdle bands that wrap around.

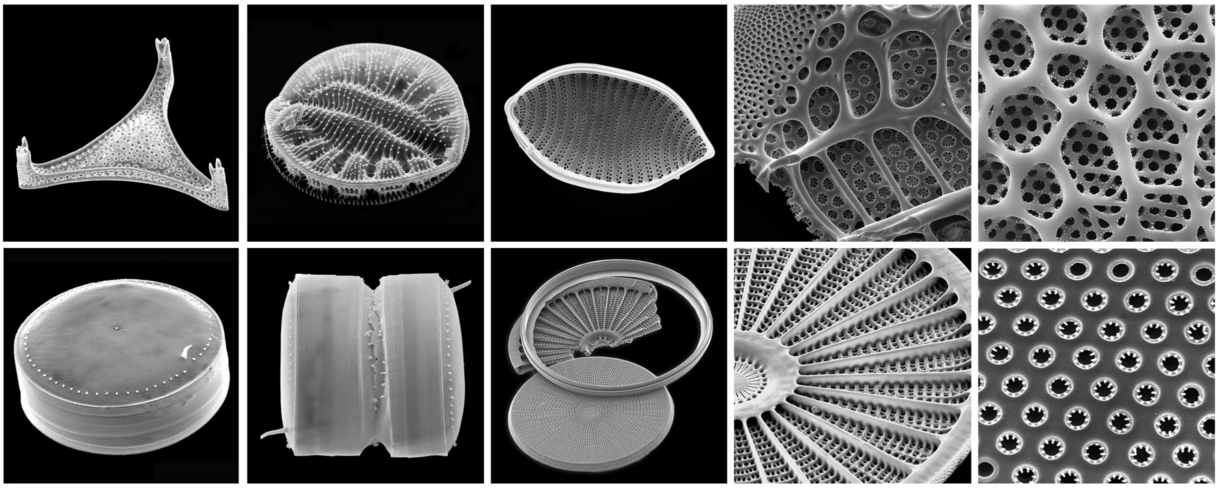


Figure 1: SEM (Scanning Electron Microscope) images of various diatoms
[Bionic Lightweight Design RG, Alfred Wegener Institute for Polar and Marine Research]

1.1. Microscopic Lightweight Structures

Diatoms are ubiquitous, inhabiting diverse aquatic environments, ranging from polar oceans to tropical freshwater habitats. Their ability to adapt to highly dynamic marine environments is demonstrated by a rich diversity of species, manifested in a wide variety of shapes, sizes and lifestyles (Figure 1). Diatoms' success as a dominating group of phytoplankton is attributed to millions of years of evolution where the optimization of their siliceous shells must have been essential for facilitating their buoyant way of life (necessary for Photosynthesis) while ensuring sufficient robustness to fend off predators (Hamm, [2]).

1.2. Research in Lightweight Architecture

Due to their visually striking designs and lightweight properties, diatoms have attracted the attention of architects and engineers who applied engineering notions and material science to understand the structural behavior of these organisms. Notable research in the field is the work of Architect Frei Otto who specialized in lightweight constructions. Collaborating closely with Biologist Johann-Gerhard Helmcke at TU Berlin [3], Otto adopted scientific methodologies to study morphogenetic processes in order to measure and illustrate diatoms' inherent structural properties. Based on Helmcke's theory, the as yet unformed diatom produces fat droplets during metabolism, which arrange themselves on the surface and compete for space, touching and deforming each other in the process (Figure 2A). Physical experiments were conducted to produce analogous forms that approximate the porous structure of diatom shells. While other concepts such as the geodesic dome bear resemblance, their direct correlation remains speculative rather than demonstrable (Figure 2 B-C) [4].

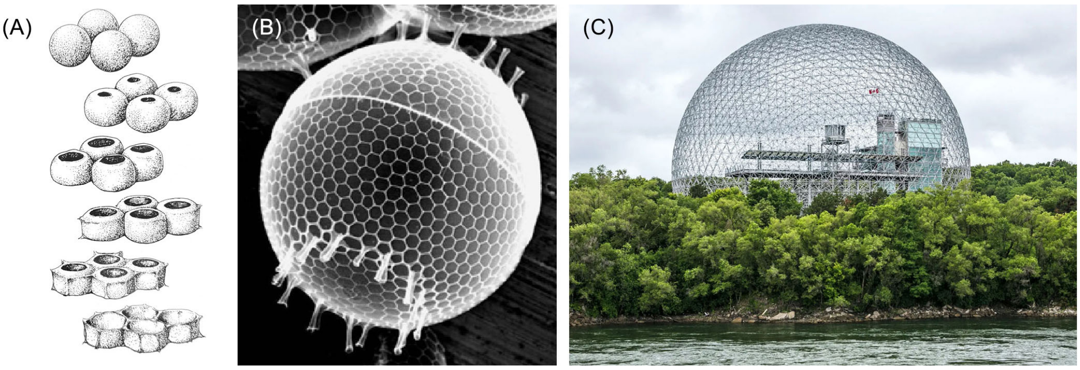


Figure 2: (A) Morphogenetic sequence from round compartments to chambered valves with a hexagonal pattern [IL 28], (B) Stephanopyxis turris, (C) Biosphere Montreal 1967 [https://re-thinkingthefuture.com]

2. Bio-inspired Structural Design

Bio-inspired design has seen numerous successes in structural engineering and optimization, but the transfer of solutions from biology remains challenging due to the risk of drawing inaccurate conclusions as the laws of similarity could easily be violated [4]. Differences in mechanical properties between biological and technical materials pose challenges for direct comparison; therefore, effective application requires consideration of functional and structural aspects beyond superficial appearances [4]. Despite these challenges, lightweight architectural design, which values elegance and structural efficiency, can derive valuable inspiration from diatoms as models. A systematic approach to utilizing these structures as design templates holds potential for innovative, holistic technical solutions.

2.1. Centric Diatoms and Radial Architecture

Diatoms exhibit remarkable symmetry in their shells, displaying radial symmetry (centric diatoms) characterized by the arrangement of features around a central point, or bilateral symmetry (pennate diatoms) which involves a mirror-image arrangement of features along a central axis [1]. The high geometric regularity in diatom shells points to an inherent constructive logic that employs repetitive units, suggesting that these complex microstructures are prepared for various loading, otherwise a weakness will be exploited by predators.

In this paper, diatoms are presented as biological models for repetitive geometric filigree structures. Their remarkable resemblance to the most fundamental and widely utilized form of man-made shell structures, the dome, along with the morphogenetic processes inherent in shell formation, call for a comprehensive analogy to be explored between diatoms and structural forms defined as surfaces of revolution (Figure 3). Among the two main groups of diatoms, particular attention is therefore directed towards the radially symmetrical centric diatoms for initial investigation. The patterns and structural principles observed in centric diatoms are subsequently applied to generic geometries representing both synclastic surfaces (a dome) and anticlastic surface (a funnel).

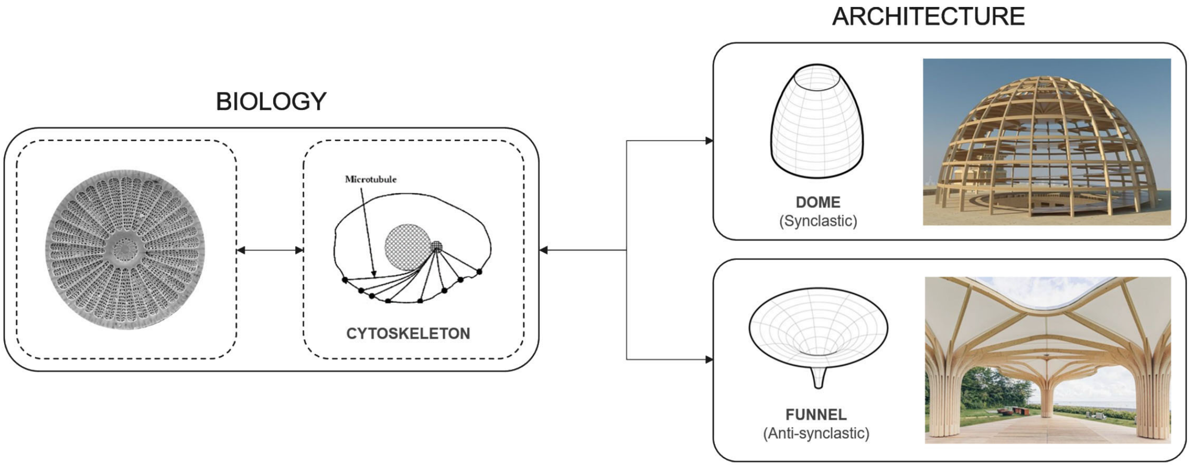


Figure 3: Diagram representing the analogy between centric diatoms and radial structures

2.2. Beyond the Voronoi

Diatoms utilize various lightweight solutions reflected by their myriad patterns. Honeycomb (regular hexagonal grids) and voronoi patterns found in diatoms such as Thallasiosira as well as other natural structures, are well established examples of efficient structures due to their optimal geometric configuration that allows for efficient distribution of stress. These patterns have successfully been transferred into technical applications and are widely used in lightweight architectural design and engineering. Nonetheless, diatoms offer a plethora of other solutions; by examining alternative models and examples of structural patterns, we expand the catalog of lightweight solutions, exposing new technical potentials and aesthetic possibilities. The following section presents a study on Asterolampra structural features, followed by their application as simplified patterns on generic radial geometries.

3. Case Study: Asterolampra

Asterolampraceae is a family of diatoms belonging to Centrales (centrics) characterized by having a star shape. These diatoms are primarily found in marine and freshwater environments. Asterolampraceae includes several genera, with Asterolampra being one of the most prominent boasting perfect radial symmetry around a central annulus, versus Asteromphalus that has an eccentric annulus [5].

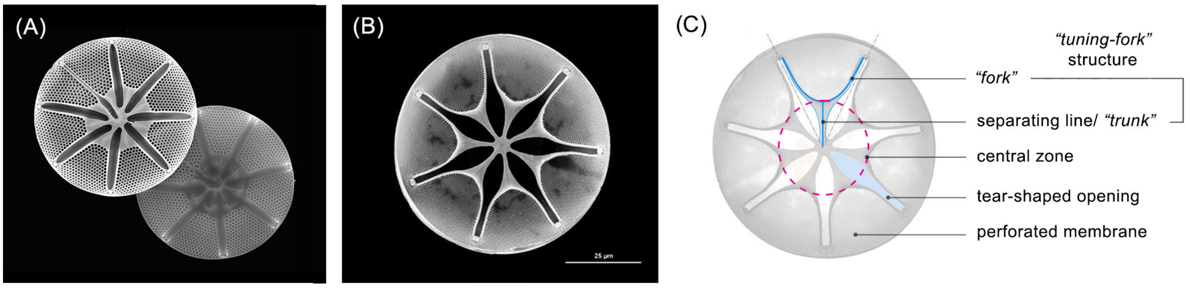


Figure 4: (A) Asteromphalus hyalinus; (B) Asterolampra marylandica; (C) Diagram of morphological features

3.1. Structural Patterns

A distinctive morphological feature of genera in this family is a tuning fork-like structure emanating from the center (Figure 4). The "tuning fork" prongs bifurcate from radially arranged supporting wall structures called separating lines [5]. This internal structure is usually obscured in SEM (Scanning Electron Microscopy) but can be seen in LM (Light Microscopy). The marginal fusion of adjacent forks forms hollow rays resembling tear-shaped openings or slits, the edges of which are seen as curved lines adjacent to the separating lines. Examining images generated through light and electron microscopy of different species (Figure 5), the following observations are made:

1. The valve has two zones of stiffness defined by a central cap from which the bifurcating structures emanate, and an ornamental porous membrane.
2. The central area including supporting walls occupies about 1/2 of the valve diameter but can vary.
3. Supporting walls may converge at the center, branch out or emanate from a voronoi arrangement.
4. "Tuning fork prongs" may have a V, U or trapezoidal shape

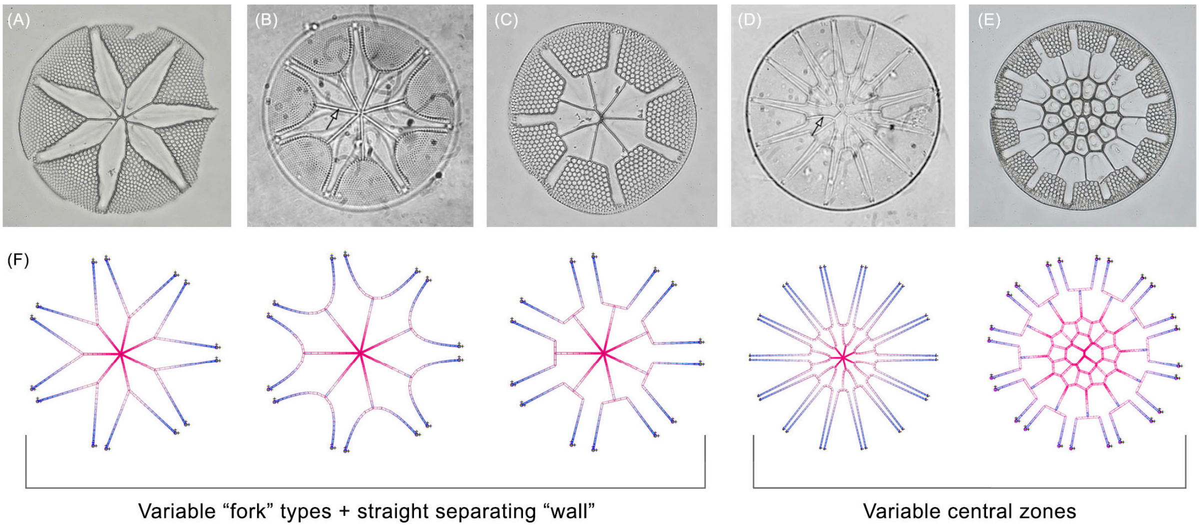


Figure 5: (A) Asterolampra uster; (B) Asterolampra marylandica (C/D) Asterolampra grevillei
(E) Asterolampra affinis (F) Parametric models representing structural patterns of various species [5]

3.2. Computational Workflow

To develop representative digital models and test their structural performance under various loading conditions, a computational modeling workflow was established using: Rhinoceros 3D/ Grasshopper, a CAD (computer-aided design) application offering parametric control over shapes, and Karamba 3D, a GH plugin utilized for Finite Element Analysis (a numerical technique for structural analysis).

3.3. Transfer of Design Principles

For this study, the main focus were the wall and fork elements and how their shapes and patterns influence stiffness. Other morphological features such as the membrane and processes (siliceous protrusions) have been omitted. Diatom patterns were read in valve view and various construction principles of the shell's main load paths were identified. The structural patterns were reconstructed parametrically. Two features define the parametric models: the arrangement of separating lines in the central zone and the shape of the fork.

The parametric patterns represent idealized or simplified versions of the actual microstructures. Design variables or parameters were determined by observed variations among different species. Variations of each and combinations were created for a comparative study (Figure 6). The skeletal networks were then projected onto a shallow dome geometry (10 m x 2.5 m) and translated into framework structures where the curved members of rectangular cross-sections would be defined in Karamba as Glulam Timber beam elements (GL36c, central members: 7.5 cm x 20 cm, prong members: 7.5 cm x 10 cm). Parameters include: polar array value, extent of central zone and spread of fork prongs. The parametric models are used to assess the varying load-bearing capabilities and structural efficiency of the different patterns and subset parts under a set of defined load cases, in this case gravitational load combined with a concentrated point load at the apex. Accordingly, the patterns may be ranked and optimized for efficiency based on reduced weight and smaller values for maximum displacement.

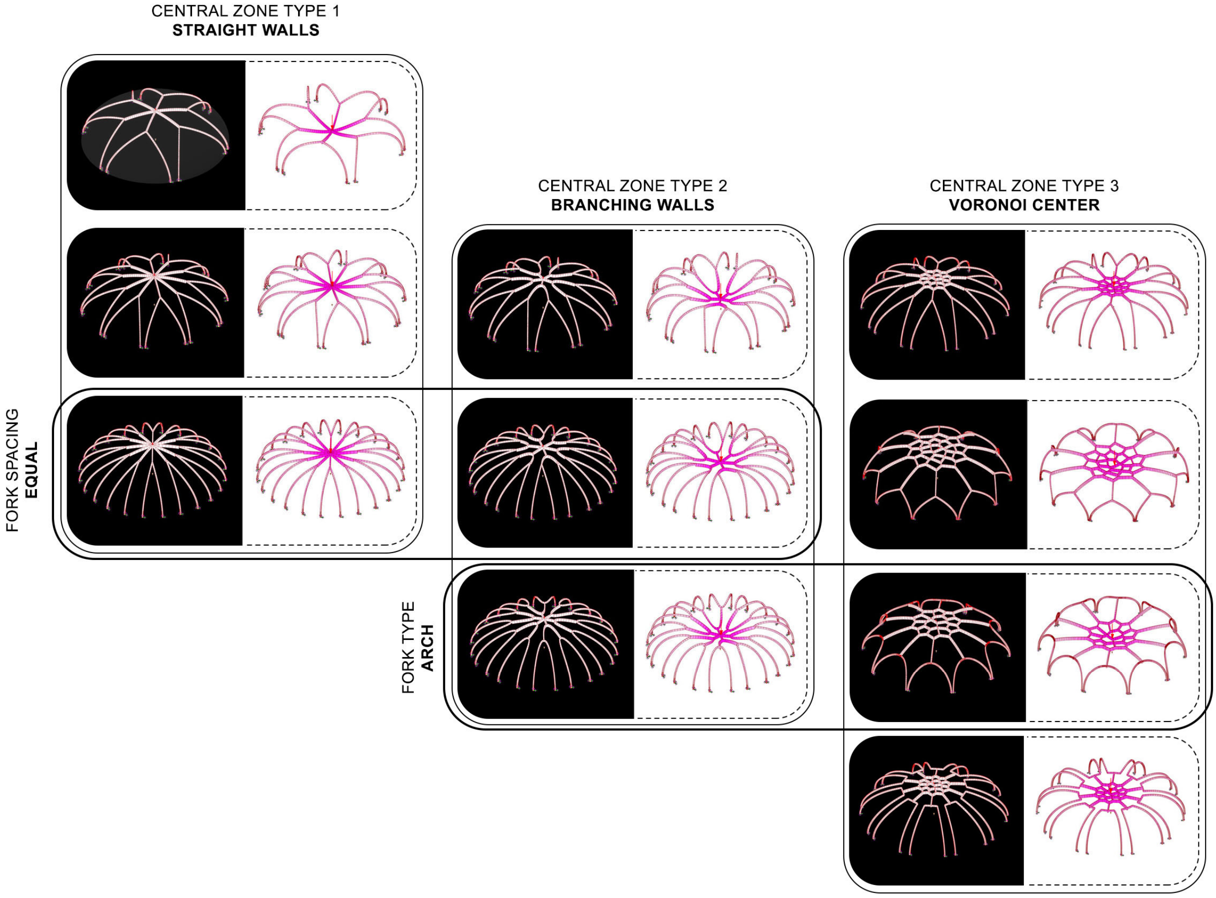


Figure 6: Parametric families of Asterolampra dome structures and their deformations (Karamba scale 50)

4. Application: Bionic Shade Structure

In the previous section, the general approach for extracting structural patterns from centric diatoms and implementing them on generic dome surfaces was presented. In this section, the same approach is adopted, this time for the design of a shade structure. The concept can be described as pushing the center of the diatom downwards resulting in a funnel-shaped minimal surface. The form of the shade structure is later adapted to fit in a bionic park in Goethequartier in Bremerhaven, North Germany (Figure 7).

Design Concept
Push down the center

3D-printed scale prototype
Funnel-shape + porous membrane

Architectural Concept
Design adaptation

Figure 7: Bio-inspired design process: from concept to adaptation

4.1. Computational Workflow

The "tuning fork" concept of Asterolampra is implemented on a base surface generated by lofting 3 input curves. The 2D pattern is described mathematically and projected on the lofted surface (Figure 8). The pattern is translated into a skeletal network or a filigree system comprising of 4 groups of structural components: the trunk, the fork, the rim and truss-like triangulations connecting the trunk members (analogous to Asterolampra's central cap). Spanning the fork flanges is a membrane surface defined as shell element. Design variables include: number of radial repetitions, spread of fork members, extent of trunk members, level of triangulation at the base and the cross-sectional dimensions of all tubular members defined per group. The canopy of the shade structure spans 8 m and the height is 5 m. The material for this structural ensemble is steel S355. The membrane is defined as ETFE.

4.2. Sensitivity Analysis

The interest in structural optimization is increasing with the continuing demand for lightweight, efficient and low-cost structures. In order to optimize the parametric structure, a preliminary analysis and understanding of the behavior of the structure and its component parts (a sensitivity analysis) were necessary. A structural analysis was set up within grasshopper using Karamba 3D. The structural groups have been assigned domain ranges for their cross sectional proportions and load scenarios similar to the ones used for the domes have been set up.

4.3. Loads

Load case combinations: LC1: G + PL; LC2: G+ WL

4.3.1. Dead Loads (G)

This includes the weight of the shade structure itself, including all structural components of the frame and the ETFE membrane.

4.3.2. Point Loads (PL)

The rim serves as a key element where the structural integrity of the entire structure is determined. By applying loads at the points where structural members connect to the rim, the analysis can assess stress concentrations and load transfers at critical points. This simulates real-life scenarios, such as live loads caused by snow or maintenance personnel exerting concentrated loads on the canopy's edge.

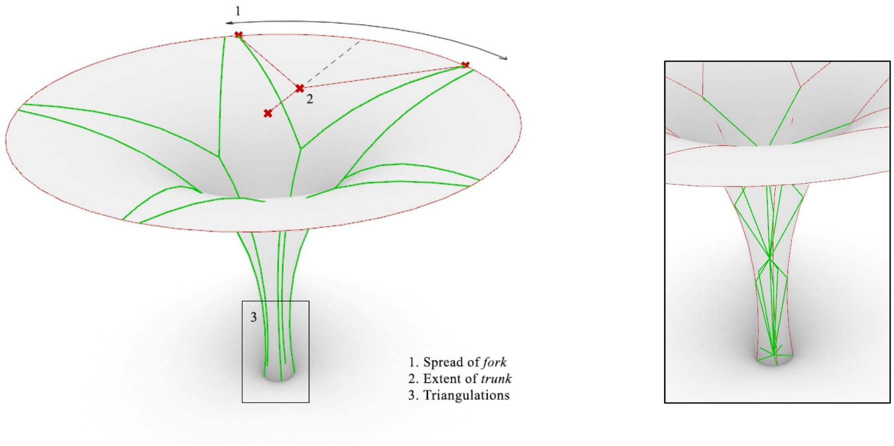


Figure 8: Parametric construction of the radially symmetrical structure (Rhino/GH).
The structure is 8 m (diameter) x 5 m (height).

4.3.3. Wind Loads (WL)

To simulate wind force, the loads to which the surface of the structure is exposed to horizontally are transferred to load bearing parts, i.e. the structural framework. The load is distributed along the structural components on one side of the model. A value of 0.391 KN/m^2 is set; Wind load is calculated by multiplying by the cross sectional (projected) area of the funnel.

4.4. Optimization

To refine the structural design of the structure and optimize cost by reducing the overall mass, a multi-objective optimization was carried out in Octopus. Structural optimization can be defined as the process of finding the optimal conditions that give the maximum or minimum value of an objective function f(x) subject to constraints in its own variable x (parameters) or design variables. Octopus takes 2 inputs: fitness criteria and genome. To determine which design variables to input as genome of the solution space, the results of the sensitivity analysis were considered in addition to design-related factors which helped determine the parameters to be fixed and define the domain ranges of geometrical parameters that influence design aesthetics. Accordingly, the base geometry was fixed and domain ranges calibrated. Finally, the design variables included the cross-sectional dimension of the fork elements, and a geometrical parameter represented by the position of the nodal junction where the trunk connects with the fork. The optimization was based on the more impacting load case (LC2) and ran for 20 generations displaying converged results. The model was then analyzed with respect to the initial design settings.

4.5. Results

Initial assessment (Figure 9) showed acceptable displacement values for the assigned system properties for both load cases. For a mass of 1250 Kg, displacement due to WL (2.33 cm) was higher than that of PL on the rim (1.48 cm), displacement upon gravity was close to null (0.6 cm). An optimized solution identified at the Pareto Front displayed slight improvement in mass and structural performance. For a mass of 1245 Kg (-0.4%), displacement due to WL was reduced to 1.97 cm (-15.5%).

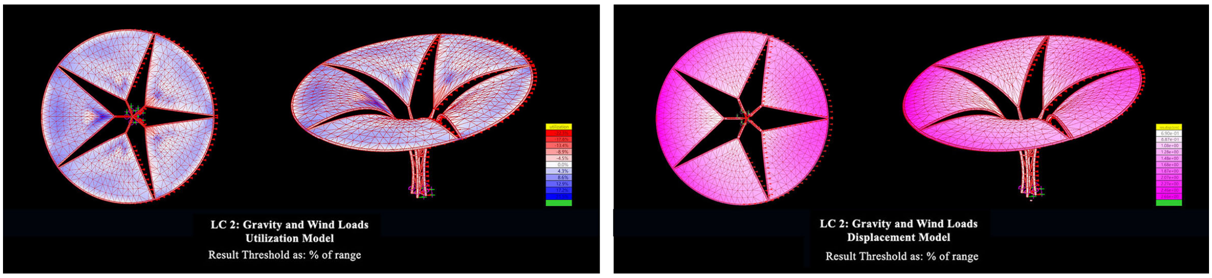


Figure 9: Utilization and displacement for LC1 (analyzed in Karamba 3D)

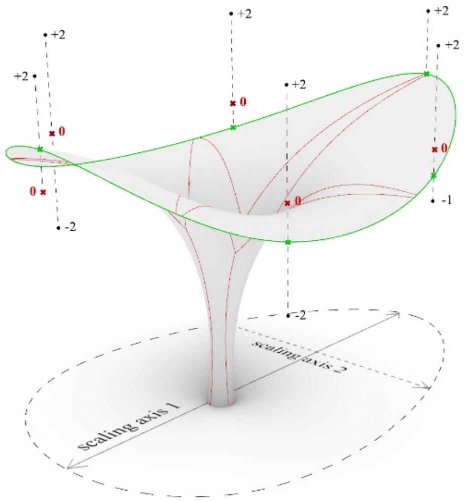


Figure 10: Parametric model of dynamic shade structure (Rhino/GH).
The new structure footprint fits within a bounding area of 10.2 m x 7.1 m (height is variable)

5. Nonstandard design (dynamic variant)

Since the initial design was radially symmetrical, it was expected to evenly distribute loads around its central axis, enhancing stability and ensuring predictable structural behavior against wind and other external forces. However, a stand-alone shade structure may typically have a non-standard design or irregular shape in order to address environmental and spatial requirements. Asymmetry in a non-uniform shape, such as an elongated or axially biased structure, can significantly impact its structural behavior. The uneven distribution of mass and forces may create uneven loading conditions posing stability challenges, particularly under wind or snow conditions. Therefore, structural analysis and optimization become increasingly critical for ensuring stability in such a case. Despite potential challenges, an asymmetrical, dynamic form offers greater design flexibility and aesthetic appeal.

5.1. Parametric adaptation

To evaluate the structural performance of the dynamic variant of the symmetrical structure, the shape of the base surface is modified such that the rim (border) is transformed into a parametrically adjustable oval-shaped, undulating curve whose center is shifted from the funnel's central axis (Figure 10), maintaining bilateral symmetry. The now asymmetrical design fits within a bounding area of 10.2 m x 7.1 m, with a variable height, and maintains the same 55 sqm footprint as its symmetrical counterpart.

5.2. Structural Analysis

The same script and general settings are used to evaluate the new structure. Same load conditions are applied and the structural behaviors are compared. The new structure displays an increase in mass and a substantial increase in displacement values for all load conditions (Figure 11): 9.21 cm (G), 10.87 (PL) and 6.62 cm (WL – wind direction parallel to longitudinal axis).

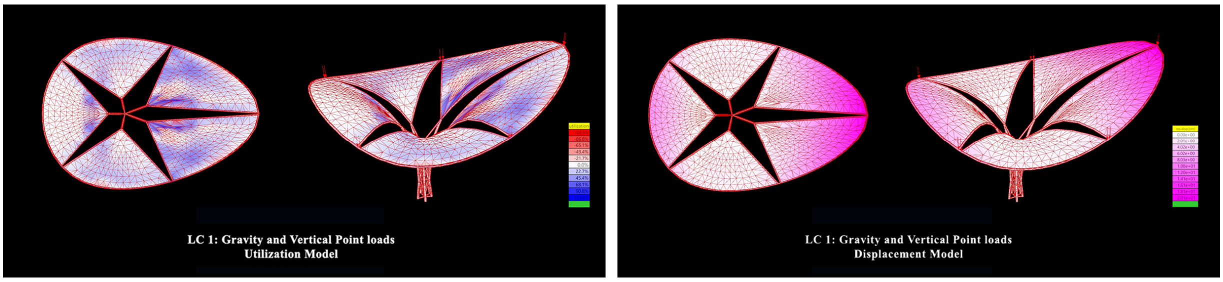
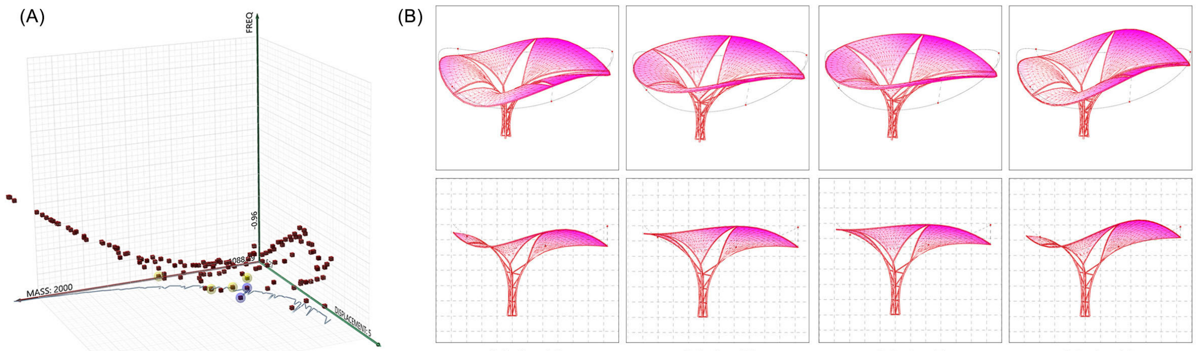


Figure 11: Utilization and displacement for LC1 (analyzed in Karamba 3D)



Solution (1)
1487 KG
LC1 disp.: 4.7 cm/ 7.7 cm
m: -11.5% dis.: -38%

Solution (2)
1506 KG
LC1 disp.: 3.7 cm/ 6.4 cm
m: -10.4% dis.: -50%

Solution (3)
1567 KG
LC1 disp.: 2.9 cm/ 4.5 cm
m: -6.8% dis.: -63%

Solution (4)
1698 KG
LC1 disp.: 6 cm/ 7.2 cm
m: +1% dis.: -34%

Figure 12: Octopus GH solution space and selected options marked at the Pareto Front

5.3. Structural Optimization

The design is again optimized based on the worst-case scenario LC1, in which the cantilevered side presents structural vulnerability. This time a geometric form-finding through structural optimization is carried out: The vertical positions (z coordinates) of the interpolated border curve control points are assumed as design variables in the optimization in addition to fork members cross sectional dimension. A domain range of up to 4 m is given for the z coordinates as a search space for the algorithm to find the optimal shape. The course of the optimization over 20 generations is shown. Four solutions at the Pareto front are identified and evaluated in terms of material and structural efficiency as well as design dynamism (Figure 12). Solution 3 registers the highest reduction in displacement values (-63%). Solution 1 registers highest reduction in weight (-11.5%) and solution 4 returns the most dynamic design.

6. Conclusion

Centric diatoms present a rich catalogue of structural solutions to consider as templates for radial framework structures. The patterns may be implemented on repetitive geometric surfaces or irregular forms. In the presented examples, structural optimization demonstrated significantly enhanced results for an asymmetrical freeform design compared to a symmetrical one. The optimization process had greater flexibility in distributing material by reconfiguring the structural elements and identified specific areas where improvements could be made to address the localized stress concentrations at the cantilever, in contrast with the symmetrical counterpart which was inherently more stable and exhibited a more predictable behavior. In either case, this interdisciplinary approach offers new opportunities for innovative bio-inspired designs for radial framework structures, with the potential to enhance structural performance, efficiency and aesthetics.

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