

Optimizing Digital Organic Freeform Modelling for Fabrication by Using Parameterization With Glass Fibre Reinforced Plastics (GRP)

A case study

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Abstract. *In the fabrication of organic free-form shapes in architecture one is constantly faced with specific planning and design challenges. This paper examines these problems as well as possible solutions for the design of a completed and built prototype using the example of an organically shaped pavilion made of glass fibre reinforced plastic modules. The paper describes which adjustments to the original design were required to take the step from “digital physicality” to “physical digitality” to realize a constructive and economically successful implementation. The solutions discussed combine modern digital software methods such as parametric design with innovative 3D modelling principles.*

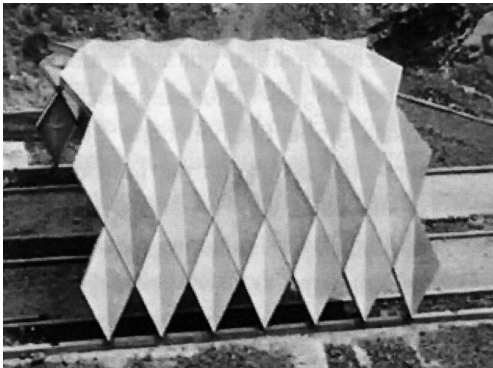
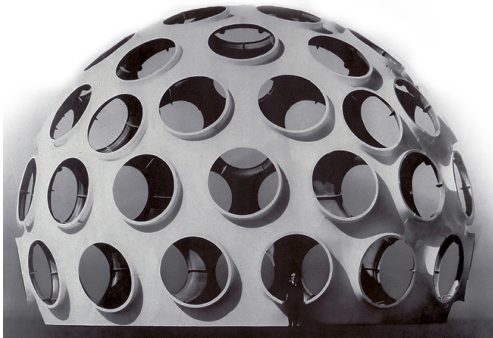
Keywords. *Digital fabrication; freeform modelling; parametric design; bionic, GRP.*

INTRODUCTION

In the fabrication of organic free-form shapes in architecture one is constantly faced with specific planning and design challenges. This paper examines these problems as well as possible solutions for the design of a completed and built prototype using the example of an organically shaped pavilion made of glass fibre reinforced plastic (GRP) modules. We show which adjustments were required to the original design to take the step from “digital physicality” to “physical digitality” to realize a constructive and economically successful implementation. The solutions discussed combine modern digital software methods such as parametric design with subdivision surface modelling principles in a NURBS geometry model.

The period from 1960-1972 was the height of architectural construction with GRP (Voigt 2007). More recently, this material has experienced a renaissance among architects for a number of reasons. The availability of computer-aided design and modern production methods now make it possible to implement new forms. In the early phase of construction with GRP such forms would not have been possible. A special role is played by parametric computer-aided design, which permits the development of new and efficient formal and constructive solutions.

In the history of architecture, there are numerous examples dating as far as back as the 1960s of GRP construction using modular principles. Formally these approaches usually implement very regular



geometric solids, such as geodesic domes (Figure 1) or regular folded structures (Figure 2) (Voigt 2007). This modular approach is particularly cost-effective because a single mould can be used for each item.

In the early phases, free-form space shells with an irregular surface curvature were often made from one piece and had correspondingly small dimensions, because a modular approach was not necessary. A more recent example is the “Chanel Mobile Art Pavilion” by Zaha Hadid Architects which has a true free-form shape made using a modular steel skeleton structure with GRP cladding panels (Figure 3). However, a mould had to be constructed for each of the 400 GRP cladding panels. (Engelsmann, Spalding, and Peters, 2010).

CONCEPT AND DESIGN PHASE

Task

As a 3D specialist in the office Pohl architects, I was responsible for the development of an experimental pavilion. The design requirements for the pavilion were to create an organic form which mimics the geometric pore structure of marine diatoms (Figure 4). The structure should inherit their positive structural properties (Figure 5).

Figure 1
Monohex, Buckminster Fuller,
USA 1965. Source: (Voigt
2007).

Figure 2
Sulfur Extraction Facility,
Renzo Piano, Italy 1966.
Source: (Linne 2010).

Figure 3
Mobile Art Chanel Contemporary
Art Container, Zaha
Hadid Architects 2008, Photo
© John Linden.

Figure 4
The diatom *Arachnoidiscus* spec. with its geometric pore structure, AWI/Michels.

Glass fibre reinforced plastic (GRP) was selected as the construction material and promised to be particularly suitable as it is light weight, has high compressive and tensile strength and, most importantly, can be formed flexibly. Fibre composite construction methods are described in (Schürmann 2007) as an evolutionary solution of nature and are particularly well suited as analogous in many ways to a bionic building. Functionally, the pavilion was primarily intended to serve as a ticket booth for an art exhibition on the artist Frank Stella in Jena, Germany, and needed to be weatherproof and transportable so that it could serve other uses. Special attention was given to producing a spectacular appearance.

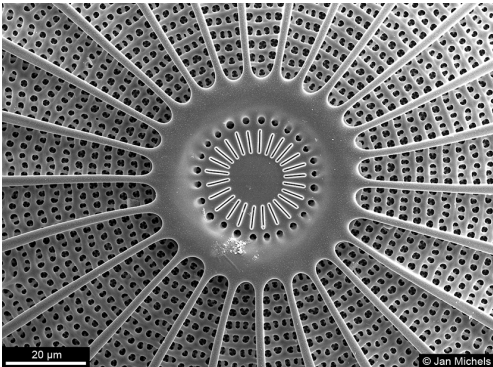


Figure 5
Various geometric shapes of diatoms preparation of diatoms from 1903 by Watson & Sons. Source: Wipeter, Wikipedia.

DESIGN AND FORM FINDING OF THE SUPPORTING STRUCTURE

Digital implementation

Initial design studies led to variants of a bone scaffold-like structure, which is formally similar to the skeletal structure of marine diatoms (Figure 7).

Structurally a branching system of hexagonal tubes was designed, between which thinner and hierarchically deeper connections should span. This structural pattern of a modified leaf structure, similar to a voronoi network, was the desired biomimetic appearance (Figure 6). The structure was initially de-

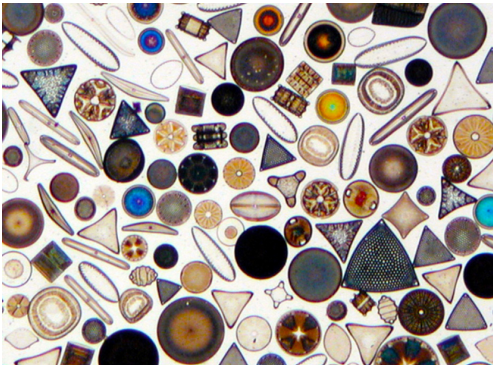
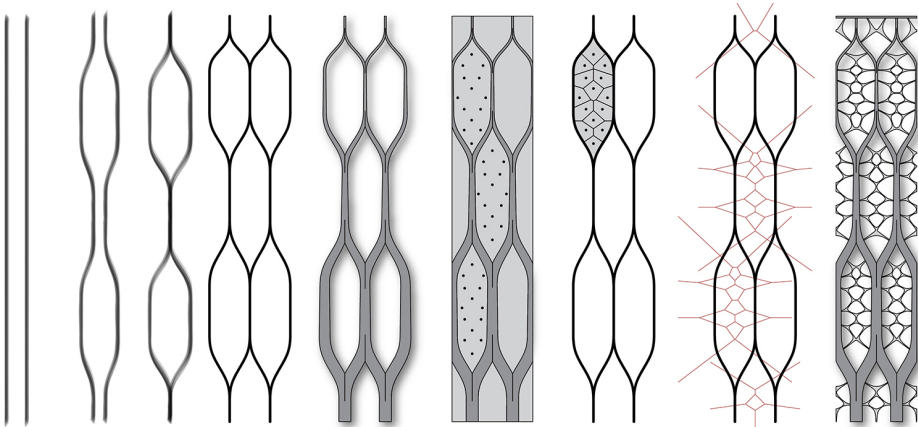


Figure 6
initial conceptual steps for development of the supporting structure.



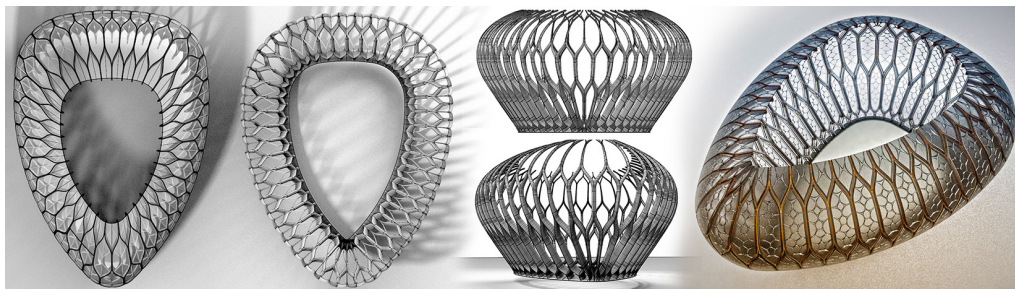


Figure 7
Initial formal studies with a skeletal structure.

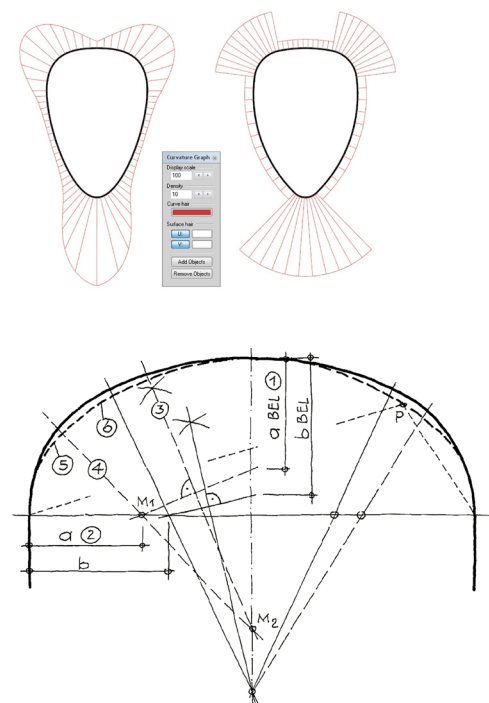


Figure 8
The curvature analysis of the base shape on the left and the constant curvature of the optimized shape right.

GEOMETRIC PROCESS OPTIMISATION AND SEGMENTATION

Modularisation of the base curve and form

An axisymmetric oval base curve defines the basic layout of the pavilion. Geometrically, an oval is described as a closed, convex twice continuously differentiable curve in the plane [1]. If this emerging form is segmented to generate subdivisions for fabrication, we would have to produce as many dies as there are wall elements, as was the case with the aforementioned “Chanel Pavilion” where each element has different curvatures and cannot be joined tangentially using identical modules. One approach to making fabrication more cost-effective is to identify a segmentation pattern of the surface that results in self-similar, repetitive modules (Eigensatz et al. 2010). However, that cannot be achieved for an ovoid body shape, since the radii of curvature of the surface are changing continuously. A method for implementing a free-form of this kind with economically available techniques and without having to relinquish the formal design idea, is already evident in similar practical engineering problems in historical architectural. The historical construction of a basket arch, for example, where the compressed form of the arch is geometrically initially half of an ellipse, was abstracted in historical building practice through tangentially touching arc segments of different radii (Figure 9)(Friedrich 1987). Even Albrecht Dürer used this method to design a Roman letter font [2]. This approach to simplifying free-forms for production is also found in contemporary discus-

Figure 9
The construction of a basket arch as an abstraction of an ellipse. Source (Friedrich 1987).

veloped as a planar net and then Surfacemorphed onto an ovoid-like basic shell in order to create the biomorphic idea. These design steps should ensure that the basic shape of the hull's rib like structure was self-stabilizing while meeting the structural requirements.

Figure 10
Parametric variations of the base curve and conditions "without kinks" and "smaller than 10 m²".

Figure 11
Parametric segmentation for panelling with 3 arc types.

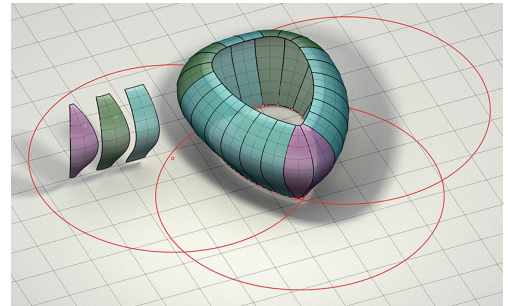
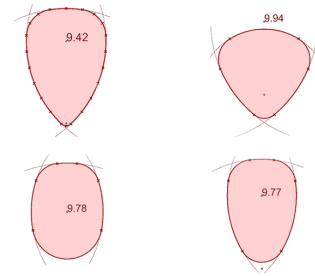
sions, for example in the chapter "simplifying complexity for fabrication" in *Scripting Cultures* (Burry 2011) or in the detailed descriptions in "Circular Arc Structures" (Bo et al. 2011).

In order to maintain the necessary design flexibility, we entered these arc dependencies into the parametric Grasshopper plugin for Rhino3D. This enabled the desired layout line to be adjusted dynamically without losing cotangency between the arc segments. The parametric solution also helped us to ensure the base of the pavilion was just less than 10m² in order to avoid the otherwise mandatory building permit for the pavilion (Figure 10).

This optimization operation allowed us to finally obtain six circular arc segments, with only three different radii of curvature. By dividing these tangentially adjoining arc segments into sections of equal length, one can map the entire base curve with just three different radii and only three types of arc segments (Figure 11).

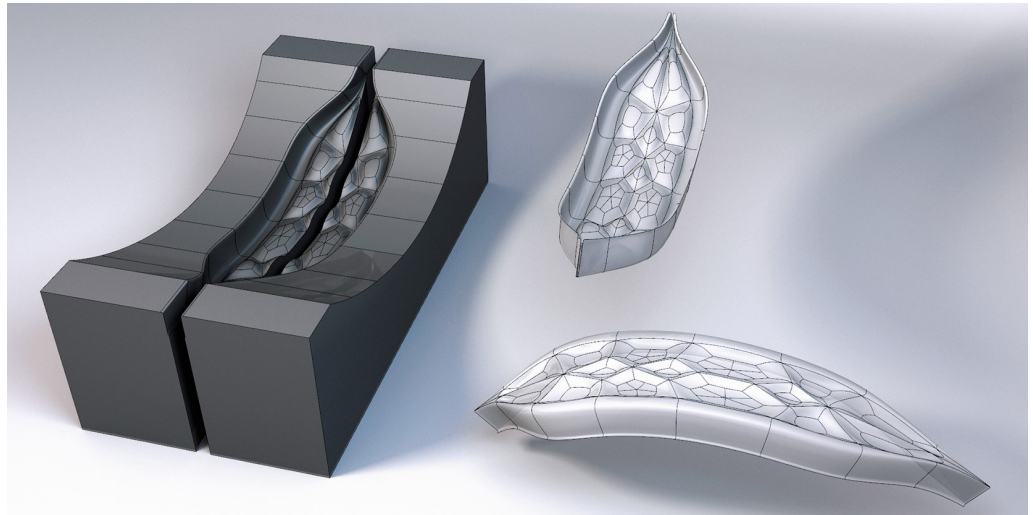
MATERIAL AND MANUFACTURING CONDITIONS

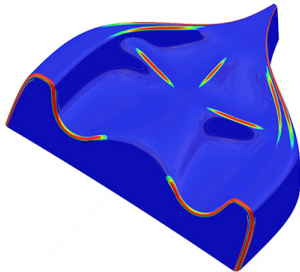
The qualities of glass fibre reinforced plastic (FRP) are increasingly being rediscovered for applications



The fabrication process used here for the enveloping elements of glass-fibre-reinforced plastic is based on in the manufacture of a negative mould. Nowadays such moulds are CNC-milled, especially where com-

Figure 12
3D model of the negative mould.





plex organic structures are concerned (Figure 12). The glass fibre fabric or fibreglass scrim is then embedded in the mould and then filled with a so-called matrix, usually an epoxy resin. After curing, the element can be removed from the mould for further processing. A fundamental factor in the production cost is therefore the making of these moulds, which are expensive to make but can be re-used often. Creating as few moulds as possible reduces the time and production costs significantly.

During the fabrication phase it was necessary to consider numerous construction-related requirements for the material-oriented design of the surface modules. In close cooperation with the company Fibertech in Chemnitz, Germany, the shape of the components was adapted during this phase to the production conditions:

- A shell shaped module should have a constant shell thickness, and show no variable wall thickness (Haferkamp 1970).
- Sharp edges within a component complicate the processing and disrupt the flow of forces (Haferkamp 1970).
- Corrugations, i.e. bulging of the walls, helps reinforce the structure (Ehrenstein 1981).
- Multi-directional curvature can also be used as a reinforcement measure (Ehrenstein 1981).
- For production methods where the matrix is introduced into a negative mould, geometric undercuts should be avoided. In this case, the form would have to be split, as it cannot otherwise be removed from the mould (Schürmann 2007).

Under these production-related requirements, the individual elements were developed as pure shell modules. The voronoi branching was integrated as corrugations in the envelope. Here Autodesk T-Splines proved indispensable. Although an established tool they are relatively new as modelling software. According to the principles of subdivision surface modeling, an underlying control cage was created which could then be transferred directly into an organic T-Splines surface (Figure 14) (T. W. Sederberg et al. 2003). Through the use of reinforcing ribs the executed wall thickness of the modules could be reduced. By extending the side flanges to a greater depth we could even dispense with an additional structural support layer. The modules rest on one another and are bonded together. The result is a self-supporting, reinforcing enveloping shell. In

Figure 13
Surface radius analysis with production critical minimum radius of red-blue of 5-10 mm.

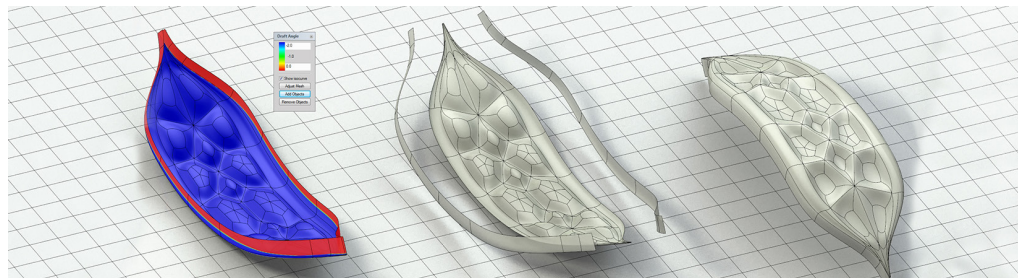
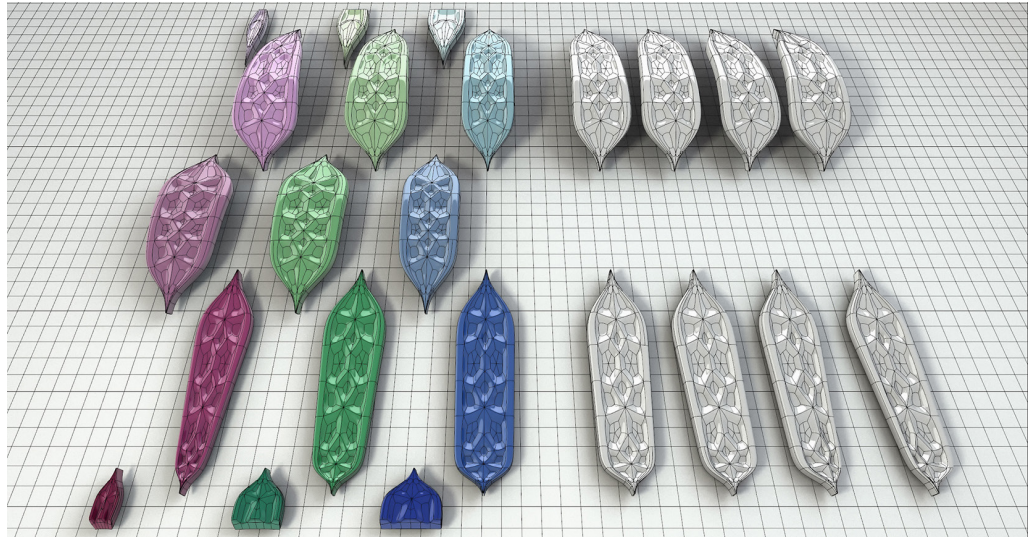


Figure 14
From left to right: T-Splines from lines, T-Splines mesh, zebra analysis, continuous T-Splines surface, NURBS.

Figure 15
Analysis of undercuts and
assembly of a typical morphed
module.



practical production tests it became apparent that for the inlaid mats a certain minimum radius inside the mould should not be exceeded, and this needed to be adjusted accordingly (Figure 13).

DESIGN AND GENERATION OF INTERFACE MODULES

Parametric conversion

Geometrically the shape-optimized shell is generated as a parametrically controllable positive-negative curved profile curve which is swept along an oval base curve (Railsweep). To simplify and subdivide free-form surfaces for practical implementation in architecture methods such as triangulation, reduction to quads or a similar method of generating flat subdivisions (Wallner et al., 2010) are used. The planar solution is ideal and economical for classical materials such as glass and steel, but is less suitable for fibreglass-moulded modules. GRP, in contrast to other materials, is often produced with even slightly curved forms to improve form stability (Haferkamp 1970).

The T-spline control cage as an organic pre-modelled module element was imported into the advanced parametric Grasshopper definition and mapped to the ovoid-like footprint using a surface morph method. Parametrically the Grasshopper definition offers the design various degrees of freedom in the design process:

- Flexible floor plan shape based on the design specifications.
- Free parametric profile form.
- Variable adjustment of module subdivisions.
- Flexible adjustment of module depth .
- Calculation of areas and volumes.
- Selective morphing of individual modular elements.

The parametrically morphed control cage could now be transferred into a watertight T-Splines surface, which in turn could be lossless-converted into a NURBS model for production (T. W. Sederberg et al. 2003). The combination of these processes creates a highly efficient workflow. A precise NURBS-transformed control module includes 33,000 control points per module. At 220 modules we would have to reckon with over 7 million control points. The

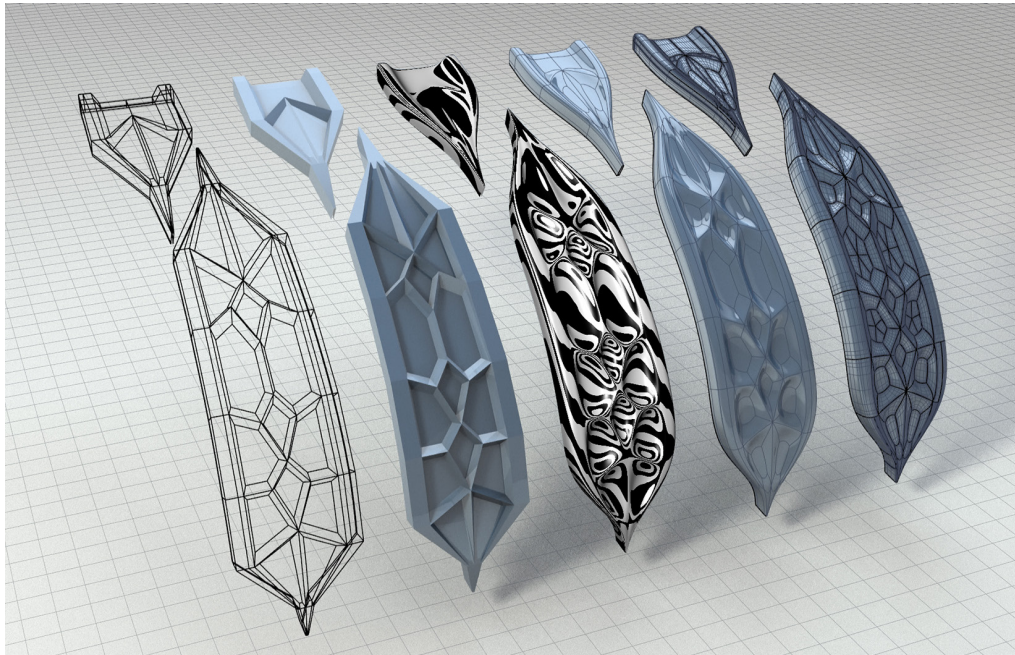


Figure 16
the entire set of morphed
surface modules used for the
pavilion.

representation of the surface as T-Splines handled both topological quality as well as memory efficiency much better (M. T. Sederberg and Sederberg 2010) (Figure 14). Due to the spatial transformation of morphing, undercuts in the individual element

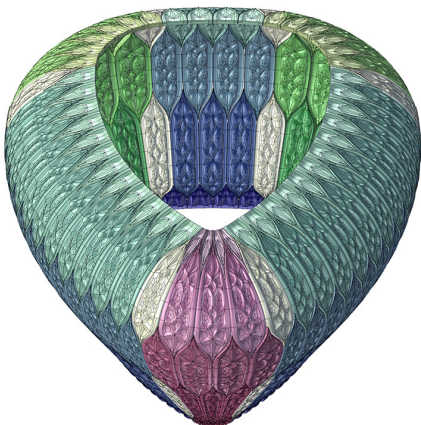


Figure 17
Same module types share the
same colour.

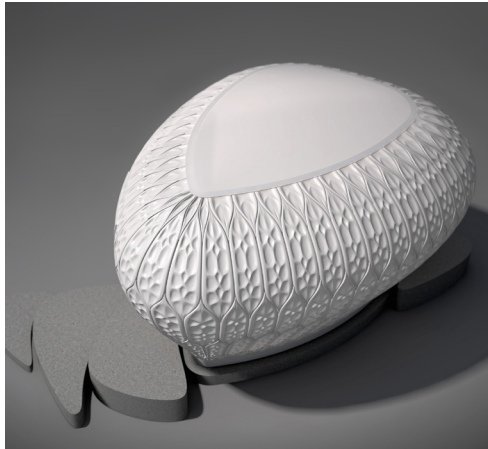
could not be completely avoided. For aesthetic reasons, the necessary joints were made as far down in the connection gaps between two different modules (Figure 15).

The final version of the pavilion as built consisted of 15 standard shapes. At the edges where the hexagonal subdivision cuts the surface at a curvature change, a further eight special forms had to be produced (shown in white) (Figure 16). These 23 moulds were then used to produce the 220 modules of the façade. The modules were assembly in a factory and transported on a trailer to the destination. To anchor the lightweight construction in place, it was mounted on a heavy load floor.

CONCLUSION

In the successful implementation of a prototypical organic shaped pavilion made of fibreglass-reinforced plastics, it was possible to reduce the design time and production costs significantly by using a combination of various computer-aided 3D

Figure 18
3D rendering of the pavilion
with its concrete base.



modelling and parametric programming principles. The approach of segmenting the base surface and then transferring this principle to the modules made it possible to reduce the ratio of total surface area to module ratio from 100% to 12% without compromising the original design intention. In fact, the integral use of parametric methods was essential to reducing the cost of the project to a feasible level.

The use of state-of-the-art modelling and design tools with innovative materials as well as drawing on bionic principles for the design opens up new avenues for the design of free-form shapes that needs further research in architectural practice. Other possible research directions include an examination of ways to further reduce the total number of moulds. Both the geometric shape and the kind of modularisation could be investigated. In the prototype, the modules are bolted together. Alternative joining methods that likewise permit on-site assembly but are more economical in terms of the transport capacity requirement could also be explored. The outcome shows that through the clever use of parameterization, entire design and architectural production processes can be adapted and reduced to a set of different families of forms that combine the same basic characteristics. Further research in this direction and a more general process of building information modelling, is worth investigating. Ultimately, the project aim to build an organic shaped pavilion inspired by a marine diatom was implemented in a means that is both effective and economical.

Figure 19
Photos of the finished pavilion
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[1] [http://de.wikipedia.org/wiki/Oval_\(Geometrie\)](http://de.wikipedia.org/wiki/Oval_(Geometrie))

[2] <http://mathworld.wolfram.com/Oval.html>