BOWOOSS – Bionic Optimized Wood Shells with Sustainability

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Summary

In architecture, shell construction is used for large spatial structures. These optimized load carrying systems possess a very high efficiency in the consumption of energy and raw materials. Pollution is reduced and the material consumption is minimized. Computer aided optimization and freeform design give the opportunity of an exact material optimization in dependency on the expected load and form. Concerning the operation, shells can be designed to be optimal in terms of energy consumption respectively solar power generation.
Until now the use of wood rather played a marginal role, implementing those examples of architecture, although this material offers manifold advantages, especially against the background of accelerating shortage of resources and increasing requirements concerning the energy balance. Until now, wood has been predominantly used as massive gluelam trusses, the possibilities for lightweight constructions, appropriate for the material involved, are still limited.
Regarding the implementation of shells, nature offers a wide range of suggestions for efficient and lightweight constructions. The focus of the examinations is on the shells of marine plankton, especially of diatoms, whose richness in species promises the discovery of entirely new construction principles. The project is targeting at transferring advantageous features of these organisms on industrial produced, modular wood shell structures. The essential challenge is to keep the complexity small in order to minimize efforts in production and assembling.
Currently a transfer of these structures in CAD – models is taking place, helping to perform stress analysis by computational methods. Micro as well as macro structures are the subject of diverse consideration allowing to draw the necessary conclusions for an architectural design. The insights of these tests are the basis for the development of physical models on different scales, which are used to verify the different approaches.

Keywords: architecture, biomimetics, bionics, wood, timber-construction, shell-construction, diatoms, renewable, sustainability

1. Introduction

1.1 Starting point

The research project focuses on the development of transferable technical solutions for wood shell constructions by applying biomimetic approaches. The economic implementation is an important aspect, developing sustainable, flexible and removable lightweight solutions for shell and folded plate constructions, using the renewable material wood. In this context, the engineering of suitable, material efficient technologies for the assembly is highly important. A further focus is the examination of life cycles in nature and the transfer of the resultant findings to the engineering.
Therefore, an important part is the use of findings of adjacent fields of knowledge, the transfer of know-how to the formation of architects and engineers, the inclusion of biologists and the integrative approach of biomimetics in favor of a decided innovation in the field of sustainable timber construction.
The research will be completed with the construction of a prototype, that will prove the technical

transferability of biolocical principles and which will help to enter a new market with a sustainable product.

1.2 Sustainability

Sustainable construction is recently gaining importance in the field of architecture and building industry. The use of renewable and recyclable raw materials is the future basis for environmental conscious construction against the background of increasing requirements concerning CO_2- and energy balance. However, the price of these limited available raw materials rises with the demand. The availability is limited to the after-expansion. A wise and efficient use of those building materials becomes more and more important.
Compared to conventional building with heavy and voluminous building elements, material-economic construction plays a rather marginal role. High production costs, caused by complex design and development as well as additional cost of manufacture and expensive assembly still prevent a large-scale application of sustainable and resource-efficient lightweight construction. Particularly in the field of timber construction, shortness of resources enforces lightweight construction. At this, especially shell and folded plate construction have proved to be adequate.
Contemporary architecture frequently orients on shell-like, biomorphic structures. The formal vocabulary of today´s architecture, developed by using computer based, generative design approaches is very expensive to implement, if traditional construction methods are used.
Actual construction systems can´t keep up with the modern design tools of the planners and don´t cope with the resulting requirements. Beneath difficulties in the traceability of these shapes, additional expenses in the production, for auxiliary constructions and the extensive assembly are high and, compared with traditional constructions, exceed the potentials in material savings. Considerations concerning the life-cycle play a rather marginal role.
Beneath its material properties, wood as building material possesses in these advisements, in consideration of the possibilities of building double-curved shapes an interesting potential. The increasing acceptance of renewable raw materials will augment the demand for wood, leading to the concentration on the issue of the availability of the raw material.
The timber construction industry still hasn´t developed suitable construction methods for the competitive implementation of contemporary formal vocabulary. Although problems with torsion and usability could be resolved by technical innovations in the last years, an essential progress could not be observed. Material efficiency and sustainability in the sense of life-cycle-considerations don´t play a namable role. Steel joints and enormous formworks are required to a high degree. In spite of the material economic advantages of shells and folded plate constructions, high expenditures for production and assembly reduce their possible application. The technical development requires new impulses, reducing the production costs, realizing multifunctional exigencies and combining variable life-cycle requirements.

1.3 Biomimetics

In nature, material-efficiency means the effective exposure with precious metabolites. Nature has generated extraordinary effective, light shells and folded plate structures, elements which are able to grow yet stable and whose potential for the technical application has to be explored.
Natural constructions have developed material efficient methods of construction, both in plant and in animal kingdom. On the one hand they employ the available raw materials efficient and dimensionally stable, they are statically optimized and they are multifunctional in many ways, on the other hand they can be built and enlarged in elementary growth processes. Examples are the shell constructions of mussels, sea urchins, etc. but also the folded plate constructions of a multitude of different leaves.
Last but not least, life-cycle plays an important role, for the grown structures are either occupied by new life-forms or they decay to their base elements from which new life originates. Shells and folded plate constructions in architecture, in contrast to natural constructions, have proved to be niche products. The examination of natural constructions leads to a thrust of innovation and helps to develop technical solutions that allow an efficient design of these surface structures. Until now, the mere technical consideration could not initiate this thrust of innovation.

1.4 Summary of the targets

In the forefront of the project, the following theses have been built, that will be verified during the research:

- Until now, building technology is affected by the use of massive building materials.
- In the light of increasing requirements concerning the CO_2- and energy balance, recyclability and resource-efficient construction methods, renewable construction materials become more important.
- The increasing demand of renewable construction materials leads to increasing prices, the availability is limited to the after expansion.
- In the future, life-cycle considerations will play a more important role, rating the construction materials of sustainable buildings.
- In this context, timber as a construction material possesses an interesting potential.
- Innovative use of wood is limited. The construction industry uses wood mainly in massive panels and voluminous gluelam trusses.
- The efficient use of the limited available construction material becomes more and more important, because the demand in other industries increases too.
- Shell constructions are light and material-efficient.
- Shell constructions can provide a high security stock for bearing loads.

2. Natural Examples

In the following some potential examples for a transfer to technical problems of the present task are briefly introduced. For shells in general, manifold examples can be found:
Sea urchins: The periodic shells are supported by an inner circular hollow skeleton, which can be, depending on the species, spherical or flattened. The shell is reinforced by radial stiffening ribs. Sea urchins can serve as an example for the optimization of the shapes of shells. Findings of the examination of sea urchin shells contributed to the design of the ice speed skating arena in Erfurt, Germany.

Fig. 1 Ice speed skating arena Erfurt, Germany (©G. Pohl)

Mussels: They are often of helical shape, caused by growth along the rim. It is a construction of natural massive shell, partially showing reinforcement elements, respectively varying thicknesses, folding or ribs, leading to an increased moment of inertia.
Tortoise shells: The shells are freeform shaped and consist of an assemblage of irregular hexagons. In this construction especially remarkable is the configuration of two layers, lying upon another. The upper shell is called the carapace, the lower shell is called the plastron. The seams of these layers are arranged in an offset pattern, which gives additional stability to the shell. A transfer to technical applications, concerning the adaption of hexagonal structures to freeform surfaces is possible. Additional, possibilities of the stabilization of joints with a low rigidity can be examined.
Beneath possible examples for the design of the shapes, the potentials for a transfer of biological structures are of special interest.

Bones: The cancellous bone is made by structures consisting of branching with three or four arms. The cancellous bone aligns alongside the distribution of forces. This leads to loadings of the framework either as tractive forces or pressure forces. Bending stress can be avoided.
Opuntias: In these cactuses, the load bearing structure is built by a fibrous, cross-linked sclerenchyma and the pressure-resistant parenchyma. This configuration can be called a natural composite.

Fig. 2 Sclerenchyma of the opuntia (©G. Pohl)

Diatoms: Only because of the immense diversity of species, uncountable basic shapes can be observed. Beside the shapes, the structures of diatoms feature a multitude of characteristics. The shells generally consist of several structures on different scales, connected with each other. This hierarchic organization leads to an increased moment of inertia as well as a reduction of material at the same time, compared with massive constructions. Further aspects that will partially be pointed out in the following are the configuration of regular patterns respectively structures on double-curved surfaces, the use of reinforcement ribs or the form-locking joints, allowing these organisms to ally in colonies.

3. Focus on joints of diatoms

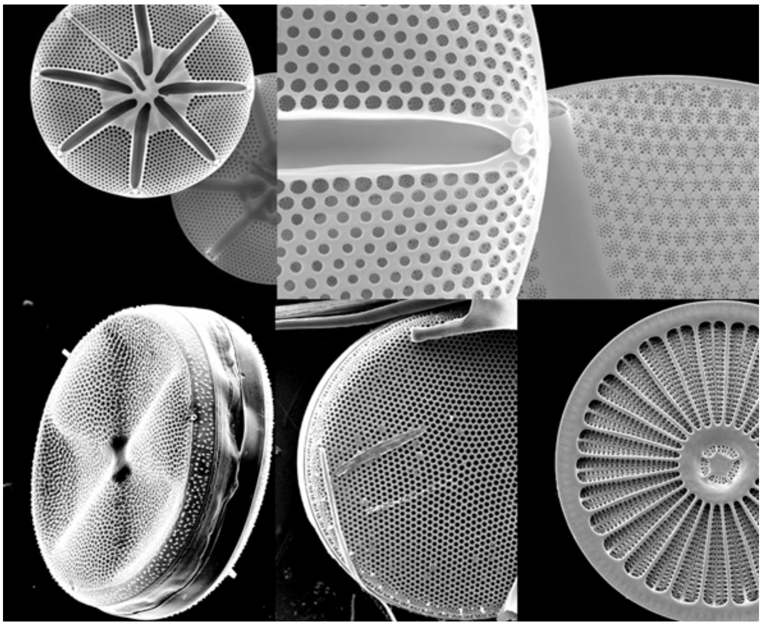

Fig. 3 Different diatoms (©Alfred-Wegener-Institut für Polar- und Meeresforschung Bremerhaven)

The countless shapes of the shells of marine plankton point out, that efficient building structures can be generated with limited resources. From time immemorial, these organisms depend on the partly very low concentration of building material in the seawater. For diatoms the substance silicate plays a major role, because it is the main constituent of the shell of the cell. With uncountable shapes and the high diversity which the diatoms have designed during the evolution, they prove, how light, material-efficient and still sturdy shell constructions can be developed with a limited available resource. The examination of the great variety of shapes promises the discovery of entirely new construction principles.

In a concrete case study the potential contained in the structural solutions of diatoms becomes apparent, which serves as an inspiration for the development of innovative joints in timber construction. Until now, in wood shell constructions, heavy loaded regions have been fortified by extraneous material, e.g. steel. Usually, these are regions, where two or more elements are connected. For this purpose, very complex laborious steel elements are needed which are expensive and prevent the potential of a better energy balance of the whole building. Last but not least, aesthetic aspects of the construction are shortened. It is the aim to realize these joints only by wooden elements, which are modular connectable. Furthermore sturdiness and long-life cycle have to be provided. By concatenating multiple single diatoms to colonies, nature shows how these joints can be realized. For diatoms, structural connections of cells play an important role. E.g., colonies provide a better protection against predators; they facilitate the reproduction and change the drift behavior, compared with solitary living cells. However the joints have to resist high external forces caused by attacking copepods or the current. Strong connections between the cells are necessary in order to absorb the distributed forces. They can be made of organic glue or by structural shaping of the shells. Glue is a disadvantageous solution, because it has to be substituted continuously, which means high energy expenditure for the cell. In contrast, structural connections need no further energy after the formation. This becomes apparent by the examination of fossil diatoms. After thousands of years, frequently the connections are still intact, although there isn´t any organic material left.

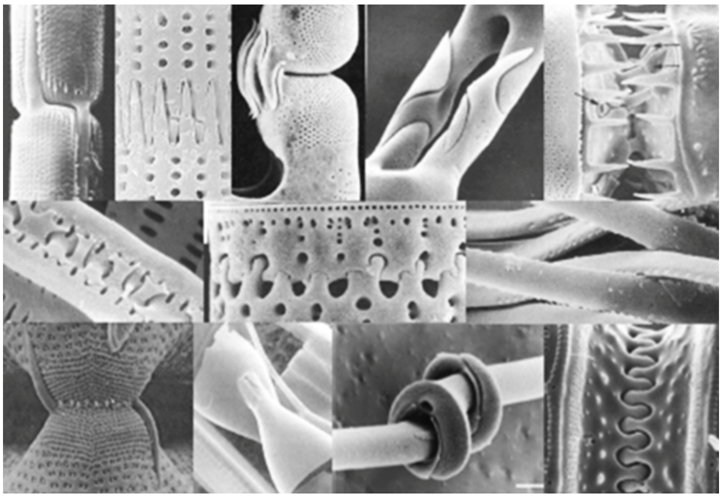

Fig. 4 Different joints of diatoms (©Alfred-Wegener-Institut für Polar- und Meeresforschung Bremerhaven)

The construction principles of several species are very similar. Especially centric species often possess intermeshing appendices at the rim of the shell. Some species have developed very complex and bizarre shapes that can be only found at this single species.

According to the construction, the different joints can be classified in three groups. Joints by tooth systems are characterized by short appendices, interlocking like gear-wheels. The second group features regions on the shell surfaces, which enable the contact with other cells. This purpose can be reached by different means, for example small appendices or elevations. The entity of other joints differs from these two general constructions and has been summarized in a third group. The mostly detected joints can be assigned to the first group with joints by toothing and short appendices. Seven, respectively eight species could be found, interlocking by this principle. The proof of several other construction principles succeeded only in single cases. Probably the distribution of these species is very limited. The summary of this analysis is that some of the examined species feature innovative and unconventional solutions for the durable connection of two cells that can outlast thousands of years in the sediment.

4. Examples for the transfer to technical applications

4.1 Opuntias / generative approach

The structure described in the following bases on the sclerenchyma of opuntias. In principle this structure is built in a configuration in which parallel longitudinal beams are connected with beams bent like sinus curves. In the model, these curved beams are designed as elastically deformed components, made of flat material. Assembled with the longitudinal beams, dimensionally stable freeform structures can be designed.

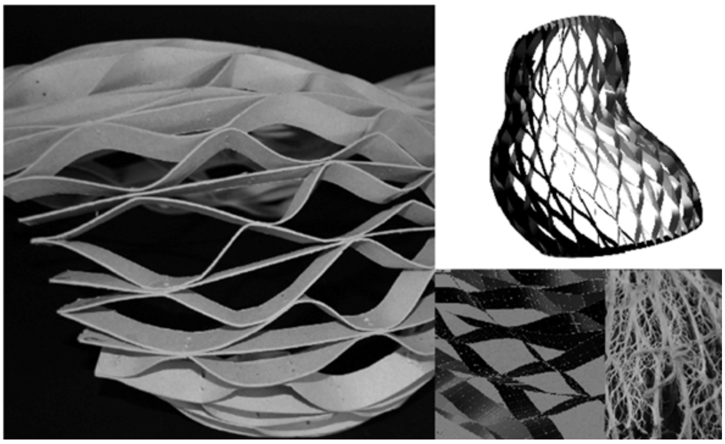

Fig. 5 Different models (©G. Pohl)

In order to automate the extremely laborious and complex construction, a parametric model was generated, using the generative, algorithmic software “Grasshopper” for the CAD-Software “Rhinoceros”. In contrast to scripting methods, the graphic user interface makes the creation of programs easier and the handling is more intuitive. Designing with this software allows to visualize the intermediary steps.

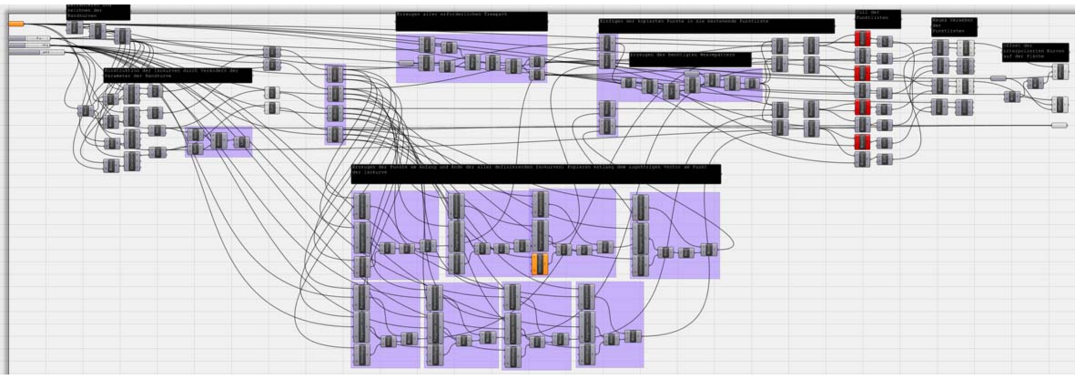

Fig. 6 Parametric construction (©G. Pohl)

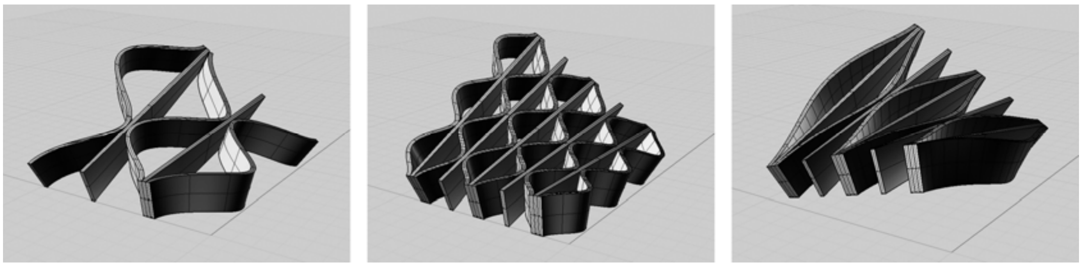

Fig. 7 Variants (©G. Pohl)

In the present case, the shape of the shell, number and size of the constructive elements can be controlled user-defined in the program. By changing shape and construction, the number of versions is unlimited.

4.2 Puzzle joints

Several diatom species feature puzzle-like joints, allowing the generation of form-locking linkages between two cells. Below, the idea is described how this construction principle can be transferred to big gluelam trusses.

The production of gluelam requires a big effort, especially in the case of curved shapes and big dimensions. The proposed method allows the modular assembly of big trusses to be made of single milled out, flat elements. These elements are arranged in an offset pattern. For the assembly, two principal methods are possible. On the one hand, the panels can be glued in the factory, on the other hand the single Elements could be completely assembled at the building site, which would lead to dramatically reduced transportation costs, however questions of assembling still have to be resolved.

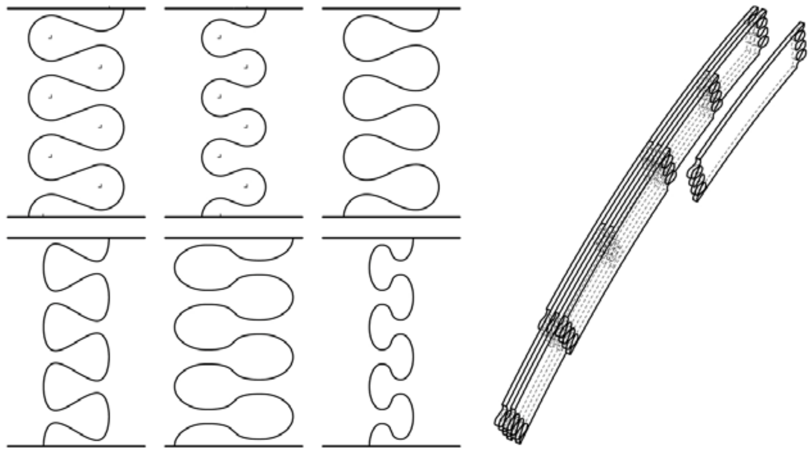

Fig. 8 Variants of the basic construction of the puzzle-like joint and assembly of a truss (©G. Pohl)

The construction of the form closure is determined by the following considerations:

- The area of contact should be as big as possible
- The steeper the gradient of the chamfer, the better the form closure works
- The teeth must not be too thin at the basis
- The contour should be as easy as possible, in order to allow an easy production

Because of considerations concerning the production and in order to minimize stress concentrations, sharp edges should be avoided.
In this context several, partly conflictive aspects have to be optimized, requiring extensive tests. At the present stage a conclusion about the optimal shape cannot be drawn.
For the both ends of two elements are laterally pushed together, enough tolerance is indispensable. If a higher expenditure in manufacturing is accepted, tapering of the notches could make the assembly easier if applicable.

5. Application

As mentioned above, the insights of the research project shall end in the erection of a prototype building. From the architect´s point of view, it is obligatory that the implementation does justice to the criteria of design. The starting point is a utilization concept for a small pavilion, the dimensions are given along general lines. The roofage shouldn´t exceed 100 m². Aspects of biomimetics should be followed as far as possible.

The applicability of the construction principles worked out during the project has been examined. Herefrom, the actual design was developed. The basic shape derives from the diatom species *asterionellopsis glacialis,* the folded plate structure of the surface, also known as miura-ori pattern, can be observed similarly in nature, for example in the foldings of the leaves of hornbeams.
By using a double axis-symmetric basic shape, the number of different building elements can be minimized, the applied structure is ideal, concerning an economic and sustainable implementation.
Improvements of the bearing strength can be achieved by supporting the surface structure by arches, which are arranged in cross direction. Thereby the folded plate structure and the arches relieve one another, allowing a material economic design of the arches.
Concerning the function, exemplarily the drainage of the roof had to be checked. Simulations revealed that water accumulated in several folds.

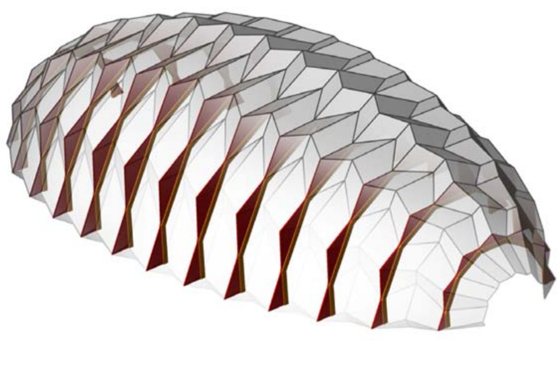

Fig. 9 Construction principle of the prototype (©G. Pohl)

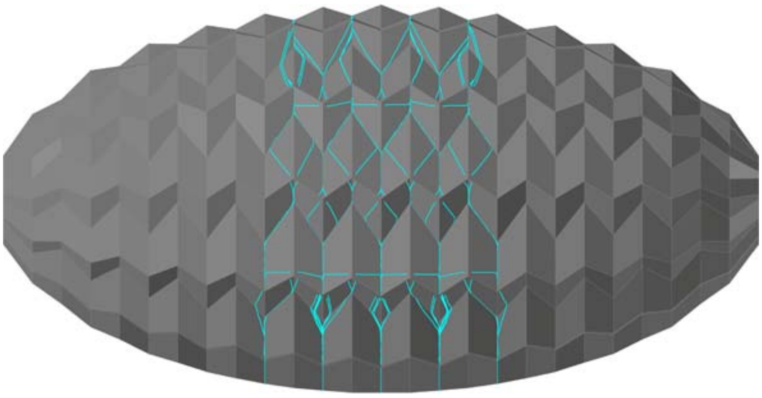

Fig. 10 Improved drainage (©G. Pohl)

Modifications of the geometry led to a correct draining of the water and the elimination of this initially existing problem.

In connection with the optimization of the geometry of the folded plate structure, the load bearing capacity was increased significantly.

Different variants of the entrance have been developed and transferred to the construction. One possibility is to swing open several plates, connected to a door around a pivot. An additional counter weight reduces the effort when opening and closing the door.

Apertures for lightening can be implemented as simple transparent plates of the structure. This allows, according to the location and orientation of the building, a precise control of the light incidence. Swiveling plates provide for air ventilation and, in combination with the apertures, shadowing.

The single elements of the folded plate structure and the arches are completely made of wood and assembled without additional metal tangs. The surface coating is white and sealing.

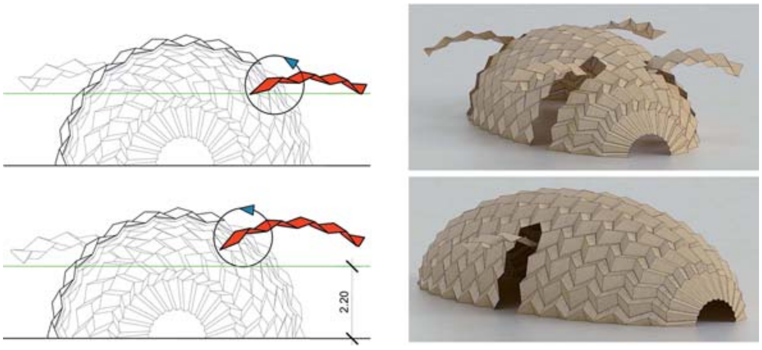

Fig. 11 Pivoted doors (©G. Pohl)

Fig. 12 Visualization (©G. Pohl)

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