Nature's Experiences for Building Technology

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Abstract

The modern building culture is in constant search for new technologies to realize the wish to design without limitations. Designers and technologists are challenged to outnumber each other with new ideas. This research can take place in different ways. Biomimicry is such a way. It is a new point of view that analyzes and imitates nature's best ideas to solve human problems; "innovation inspired by nature." However, some of these studies in the field between nature and technique have been undertaken earlier by other scientists such as Frei Otto. The technology of Biomimicry can be applied in different areas such as in building technology.

The importance of mathematics in certain fields such as physics and architecture has been known for a long time but recently its power has also been discovered in biology and nature. This paper gives a short analysis of mathematical patterns and structures in nature in order to find the opportunities of using these patterns and structures in building technology. To achieve this goal this paper shows examples of these patterns and structures already used in building technology in order to find possibilities and challenges for it in the future. For example, a nature's structure, like a human bone is used to develop a concrete bone-like façade element.

Introduction

The word Biomimicry originates from the Greek word bios, meaning life, and mimesis, meaning to imitate. Biomimicry is a new discipline that studies nature's best ideas and then imitates these designs and processes to solve human problems. You can see it as "innovation inspired by nature." See [1]

"*As you will see, "doing it nature's way" has the potential to change the way we grow food, make materials, harness energy, heal ourselves, store information, and conduct business."* Janine Bensius in [2]

Why biomimicry? Nature is a genius. To survive, nature needs to solve lots of problems. Evolutionary survival of the fittest makes animals, plants and microbes the real and perfect engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth.

We are already learning from nature, for instance, how to harness energy like a leaf, grow food like a prairie, build ceramics like an abalone, self-medicate like a chimp, create color like a peacock, compute like a cell, and run a business like a hickory forest. The conscious emulation of life's genius is a survival strategy for the human race, a path to a sustainable future. The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.

Application of biomimicry

The method. If we want to consciously emulate nature's genius, we need to look at nature differently. As Janine Bensius, co-founder of the Biomimicry Guild (see [3]], mentions in her book '*Biomimicry: Innovation Inspired by Nature'* (see [2]) there are two approaches for using biomimicry:

a) In the biology-to-design approach, a biological phenomenon suggests a new way to solve a human design challenge.
b) In the design-to-biology approach, the innovator starts with a human design challenge, identifies the core function, and then reviews how various organisms or ecosystems are achieving that function.

On the first page of her book Ms. Bensius also shows that we can use nature as model, measure, and mentor.

a) *Nature as model.* Biomimicry can be seen as a model, which we can use to solve human problems. The Biomimicry Guild and its collaborators have developed a practical design tool, called the Biomimicry Design Spiral, for using nature as model. An example is the solar cell, inspired by a leaf.
b) *Nature as measure.* Biomimicry uses an ecological standard to judge the sustainability and rightness of our innovations. After 3.8 billion years of evolution, nature has learned what works and what lasts. Nature as measure is captured in Life's Principles and is embedded in the evaluate step of the Biomimicry Design Spiral.
c) *Nature as mentor.* Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but what we can learn from it.

Application areas. Biomimicry is interesting for innovators from all different disciplines such as life-engineers, managers, designers, architects, business leaders, and more. Janine Bensius mentions in her book the differentiation of the food industry (chemistry), sustainability, the manufacturing industry (industrial design, architecture), the medical industry, information science and management. In this paper the focus will be on the inspirations of biomimicry as nature's patterns and the manufacturing industry. In modern architecture the architects try to find the limitations, and often mathematical patterns turn out to be the answer to many problems.

Mathematical patterns, nature and Architecture

Recently the power of mathematical patterns has been discovered in biology and nature. Some phenomena that one believed to be owing to chance or to the action of genes are revealed to be the consequence of mathematical dynamics. Some of these phenomena are shortly described in this chapter, focusing on patterns and structures.

Phyllotactic patterns. Phyllotactic means literally the arrangement of leaves. The arrangement of leaves of plants is not exactly arbitrary, but there are different phyllotactic patterns. These patterns show us that nature even understands mathematics; for example the Fibonacci numbers. Mathematically, all these patterns are types of lattices (see [5] and [6]).

The arrangements of leaves fall into 4 main categories: spiral, distichous, whorled, and multijugate (see figure 1, 2, 3 and 4). Spiral arrangements are most frequent and they are classified by the number of spirals (parastichies) they exhibit. The number of visible spirals (parastichies) in spiral arrangements are most often Fibonacci numbers (1, 1, 2, 3, 5, 8, 13, 21 ...)

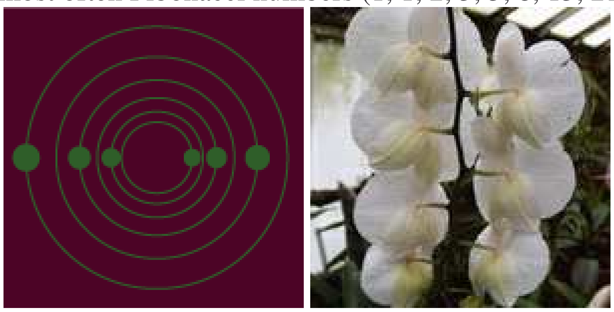


Figure 1: *The distichous phyllotactic*

Figure 2: *The whorled phyllotactic*

Figure 3: *The spiral phyllotactic*

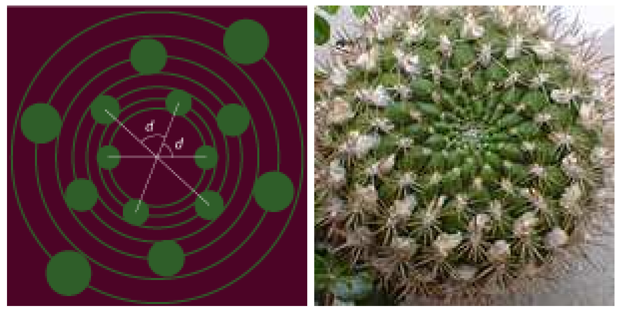


Figure 4: *The multijugate phyllotactic*

The recognizing of mathematical patterns in nature can make biomimicry more understandable and useful for building technology and architecture.

Honeycomb. The honeycomb is a structure that consists of cells with the shape of hexagons, which are made of natural wax. The cells are used for the grubs or as depository for honey and pollen. Hexagonal structures do appear a lot in nature (see figure 5). The internal angles of a regular hexagon (one where all sides and all angles are equal) are all 120°. It has 6 lines of symmetry. Like squares and equilateral triangles, regular hexagons fit together without any gaps to tile the plane (three hexagons meeting at every vertex), and so are useful for constructing tessellations. The cells of a beehive honeycomb are hexagonal for this reason because the shape makes efficient use of space and building materials. (see [7])

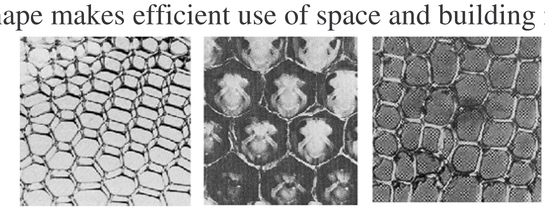


Figure 5: *left: Hexagonstructure in soap. Middle: Hexagonstructure in honeycomb. Right: Hexagonstructure in cellular tissue of plants.*

Because the hexagonal structure is so strong, stiff and light in weight, it’s a commonly used structure in building technology products. Examples of products in building technology with the use of honeycomb as the structure are temporarily floors, walls, doors and the shelter of mechanical filters.

Figure 6: *Product examples with honeycomb, see [8]*

Snail-shell. In figure 7 a spiral is drawn, in the squares, a quarter of a circle in each square. The spiral is not a true mathematical spiral (since it is made up of fragments which are parts of circles and do not go on getting smaller and smaller) but it is a good approximation to a kind of spiral that does appear often in nature. Such spirals are seen in the shape of shells of snails and sea shells and in the arrangement of seeds on flowering plants too.

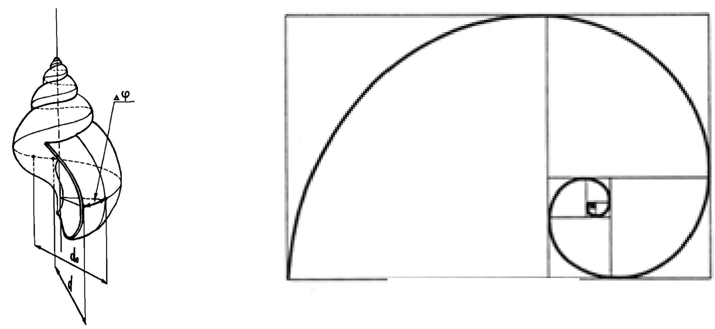


Figure 7: *The growth of a snail-shell by the golden ratio spiral. See [7]*

The spiral-in-the-squares make a line from the centre of the spiral increase by a factor of the golden number in each square. So, points on the spiral are 1.618 times as far from the centre after a quarter-turn. In a whole turn the points on a radius out from the center are 1.6184 = 6.854 times further out than when the curve last crossed the same radial line.
Example of use of the pattern found in snail-shells, like the mollusk shells are the fans, propellers, impellers, and aerators designed by PAX Scientific (USA), see [1]. A three-dimensional logarithmic spiral is found in the shells of mollusks, in the spiraling of tidal-washed kelp fronds, and in the shape of our own skin pores, through which water vapor escapes. Liquids and gases flow centripetally through these geometrically consistent flow forms with far less friction and more efficiency. Computational Fluid Dynamics and Particle Image Velocimetry tests showed the technology's streamlining effect can reduce energy requirements in fans and other rotors from between 10 and 85%, depending upon the application; the fan blade design also reduces noise by up to 75%. The first air-handling products scheduled for release are fans in computers, auto air-conditioners, and kitchen range hoods. The PAX streamlining principle could also lead to improvements in industrial mixers, water pumps, marine propellers, and devices for circulating blood in the body.

The pattern can not only be found in the physical shape of the shell but also in the material. For instance the use of nacre; the iridescent lining you see on the inside of an oyster, mussel, or abalone shell. By analyzing the way this layer is built up, experts made a new material for light weight constructions.

Animal-skins. Animal skin patterns in general seem intricate and diverse, but theoretical studies suggest that most patterns can be derived from general mechanisms. The theoretical mechanisms are most commonly based on reaction diffusion equations. Although little is known about the underlying molecular mechanism, many theoretical studies suggest that the skin patterns of animals form – through a reaction-diffusion system - a putative ‘wave’ of chemical reactions that can generate periodic patterns in the field. This idea had remained unaccepted for a long time, but recent findings on the skin patterns of fish have proved that such waves do exist in the animal body. (see [8])

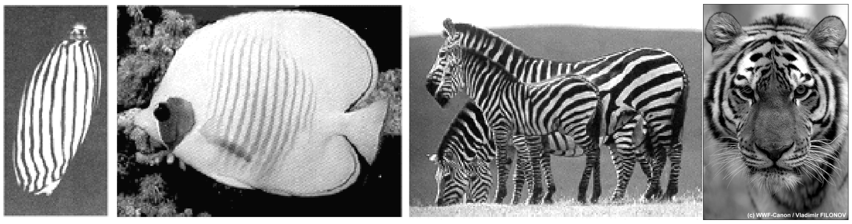


Figure 8: from left to right: *The external pattern of a shell, a tropical sea fish, zebra and a tiger*.

Patterns on the skin of animals are mainly used for warning, defense or camouflage. Patterns in the architecture are used mainly for esthetical (see figure 9) use, but sometimes also to blind the surrounding. (see figure 10)

Figure 9: *Swiss Re London*

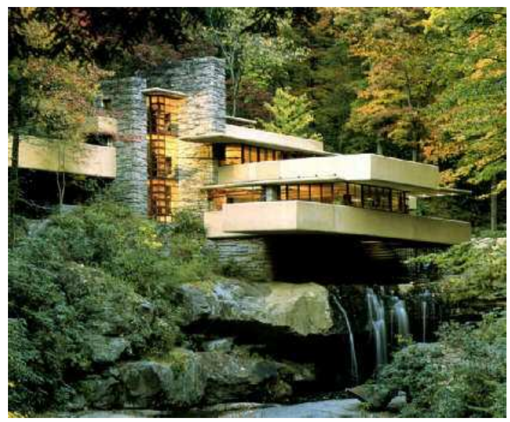


Figure 10: *Falling Water by Frank Lloyd Wright*

Nature as a model, measure and mentor

In architecture there are already some examples of concepts inspired on nature. For example the amphibian façade, that has a different color, by a different mood, or by a different angle of sunlight. But most examples are just inspired by aesthetical points of view.
But one of the best examples of biomimicry in architecture is the Eastgate Building in Harare Zimbabwe. This building uses dramatically less energy by copying strategies of natural systems, see [9].

The Eastgate building is the largest shopping centre without an air-conditioning system; the building only uses natural ventilation. The heating and cooling system is based on the principles of a local termite mound.

Termite mound. Termites build nests, inside growing or fallen trees, underground, and in above-ground mounds which they construct, to house their colonies. The shape ranges from somewhat amorphous domes or cones usually covered in grass and/or woody shrubs, to sculptured hard earth mounds, or a mixture of the two.
The termite can be seen as a master architect. Termites are blind, but with their highly developed olfactory sense, which is a sense of smell and sensitivity for vibrations, no other insect or animal approaches the termite in the size and solidity of its building structure. Comparing termites with humans, the relative size of a single termite nest is the equivalent of a 180 story building--almost 2000 feet high. How is it possible that this tiny creature has the engineering know-how to erect an edifice of this magnitude? Obviously this knowledge is innate to the

termite. The process of construction, the materials and correct combination of materials to yield an elegant, structurally efficient and durable structure is very inspiring.

Figure 11: *A termite mound*

The sculptured mounds sometimes have elaborated and distinctive forms, such as those of the compass termite (Amitermes meridionalis & A. laurensis) that builds tall wedge-shaped mounds with the long axis oriented approximately north-south. This orientation has been experimentally shown to help in thermoregulation.

The column of hot air rising in the above ground mounds helps to drive air circulation currents inside the subterranean network. The structure of these mounds can be quite complex. The temperature control is essential for those species that cultivate fungal gardens and even for those that don't, much effort and energy is spent maintaining the brood within a narrow temperature range.

Mounds built by African termites inspire new types of buildings that are self-sufficient, environmentally friendly and low-cost. The termite mounds provide a self-regulating living environment that responds to changing internal and external conditions.
The mound exists by an extensive network of tunnels, see [10]:

- Central chimney
  a large vertically oriented void above the nest. This chimney is not open to the outside but covered with a porous layer of soil.
- Surface conduits
  Narrow channels below the external surface which rum vertically along the complete height.
- Lateral connectives
  These connect the surface conduits with the chimney.

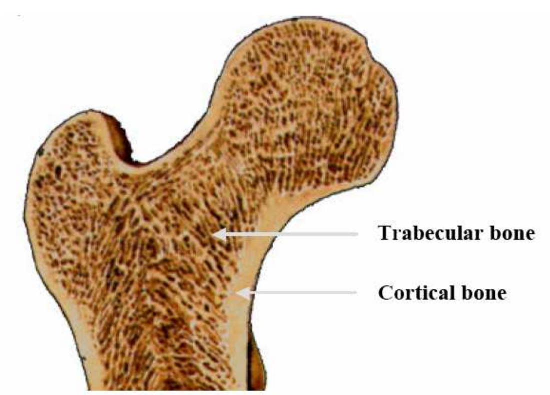
Underneath the mound, the termites have underground space which they use as their living area. This area is the foundation of the mound with the difficult construction consisting of a web of pillars.
While working, the termites produce heat, which will be driven through the surface conduits where heat and water vapor will be exchanges with the atmosphere. The refreshed air skins down into the cellar which will cause a circulation flow. But not only the circulation but also dynamic pressures, generated by the chaotic fluctuations of wind speed common in the outdoor environment, act upon the mound.
Researchers are now investigating whether similar principles could be used to design buildings that need no or few mechanical services, such as heating and ventilation, and therefore use less energy than conventional structures. Digital scanning of the termite mounds has allowed their three dimensional architecture to be mapped in an unprecedented level of detail, providing a computer model that will help scientists unravel the mystery of how the mounds are made and will offer a platform for further studies.

The Eastgate Building. Termites in Zimbabwe live off fungus that they farm inside their mounds. This fungus must be grown by exactly 87 degrees (f), while the temperature outside the mounds, fluctuates from 35 to 104 degrees (f).The architect Mick Pearce used this ventilation strategy in coorporation with engineering office ARUP for the design of the Eastgate Building. The result is a sustainable building that uses less than 10 percent of the energy of a comparable sized building.

Figure 12: *left: the outside of the Eastgate building*
right: the inside of the Eastgate building

The Human Bone. In figure 13, a section of a human femur indicates the two different types of human bone. The outer zone of the bone is made out of cortinal or compact bone. In figure 14 the highly complex structure of struts and plates of this type of bone is shown at a microscopic level. Evolution has proven that the microscopic geometry of human bone is able to bear weights and at the same time to be light in weight. This quality, in combination with the attractive image of it, has lead to the decision to apply this structure into building technology as a façade element.

Georg Zimmermann from University of Kassel, Germany is exploring the structural and geometrical potential of Ultra High Performance Concrete (UHPC) and this has lead to structures that closely resemble bones. The growing interest in free formed structures in contemporary architecture conflicts with the traditional casting processes of this concrete. To desire to combine the physical and structural qualities of this material with the esthetical qualities of free formed architecture sparks researchers to strive for new methods to produce these types of elements with concrete.



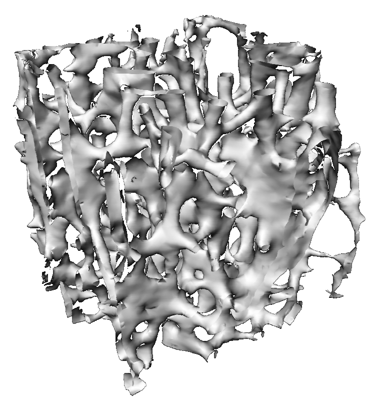


Figure 13: *Section of human femur* **Figure 14:** *Microscopic section of trabecular bone*

Mark West from C.A.S.T. (Centre for Architectural Structures and Technology) and the University of Manitoba, Canada has taken a different approach for producing free formed concrete structures. By making moulds out of membranes that deflect under the weight of wet concrete new opportunities arise for engineering and construction technology and a completely new vocabulary in architectural expression can be developed. The deflection of the material under gravity results in structurally efficient variable section members. This reduces the dead weight of the elements and saves material expenses. In Figure 15 an example of this method can be seen in which a load bearing column is produced. This work has been an important inspiration in our search for a method to produce a bone structure as a façade-element.

Figure 15: *Fabric column formwork awaiting concrete placement (left) and column after cast*

To lower the barrier for such elements to be applied in buildings, it is important to let the thought go regarding production complexities and to lower the production costs. More value can be added when the concrete is used as both an architectural as well as a structural element. In nature bone structures are used to build skeletons. It is able to bear the weight of the human body and at the same time it is relatively light. This property has been an interesting starting point for making a technology transfer from nature to architecture by building a concrete bone structure that functions as load bearing and space dividing element with a distinguished architectural expression.

The approach of the production process of free formed concrete elements has usually been influenced by the traditional method of casting concrete into stiff moulds. In most cases this has lead to very complex and labor intensive production processes resulting into rather irregular concrete surfaces. In this project a different approach towards casting concrete is chosen to develop a less complex production method that results into smoother surfaces.

To achieve this goal a mould has been made out of EPDM rubber. (figure16) Sheets of this material were locally pressed together with wooden discs. In the process of casting concrete the elasticity of the material under influence of the concrete pressure leads to deflections. By being able to control these deflections up to a certain level, it is possible to produce elements that resemble the microscopic bone structure up to a satisfying level. The research that has been done has lead to a mockup of a façade element out of fiber reinforced concrete (figure 18). An important difference with our work is that both Zimmerman and West use the primary casting material to achieve the desired form where we achieve our form by modifying not the primary casting material (EPDM rubber) but its support (wooden discs).

Figure 16: *Mould of façade element*

The façade element is divided into three separate sections. The inner layer functions as the bearing structure. Trough a steel connection element a second half layer and a third half layer is placed (see figures 17 & 18 below). Between these last two elements a cavity remains which functions as a thermal break that is filled with a transparent sheet that is pressurized.

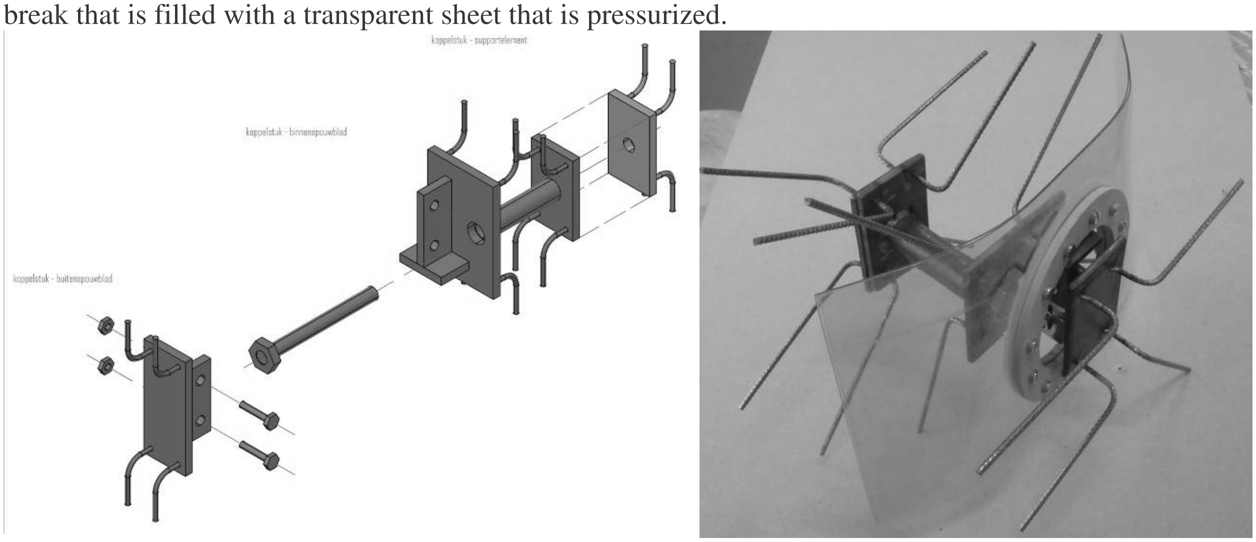


Figure 17: *Anchoring the different sections*

This division increases its functionality in relation to the building process. The first element is placed during construction of the bearing structure, while the finish element is placed later in the process, when the façade will be closed.

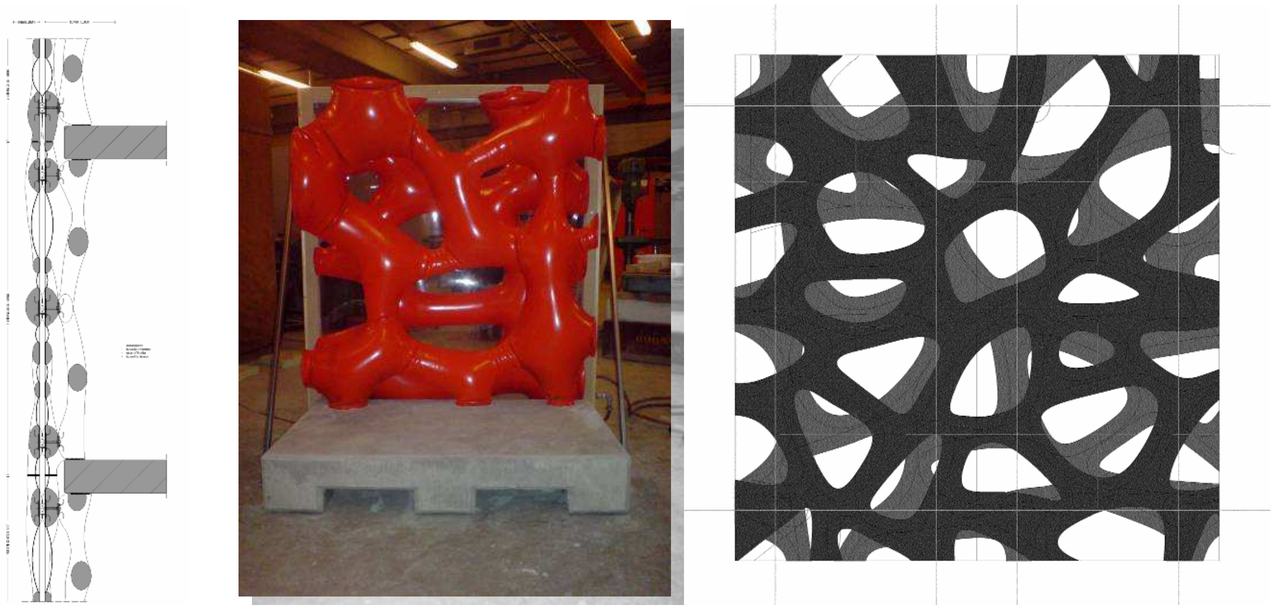


Figure 18: *intersection, mock up, design layout*

Conclusions

Nature can be seen as a model, measure and mentor for engineers. Looking in what way nature solves different problems can help us with our own questions.
In architecture we have made use of mathematical patterns for years. It gives structure to the building environment and to the site of façade. Mostly mathematic patterns are used for aesthetic reasons, but also for analyzing a design and making it possible to find new possibilities for new designs.
In nature mathematical patterns can constantly be found, for instance the Fibonacci numbers in flowers and the Golden ratio in the body of animals. To learn from nature we can analyze these and other patterns, with the help of mathematical principles nature can become readable and reflected on the building environment. By combining biomimicry with mathematic patterns for building technology some benefits can be found. We can build more sustainable buildings, save energy, cut material costs, and minimize waste. By making use of structures deriving from nature, like the human bone, it should be possible to construct forms that have an innate optimal geometry. The use of concrete in these structures enables architects to use free formed elements not only as an esthetic feature and gives them the opportunity to integrate the load bearing function into it. The mock up has shown a fragment of the potential that lies in these kinds of structures. An important role in the further development of these structures lays in possibilities of fiber reinforced concrete.
There exist also some limitations in using biomimicry. In the traditional conversional building technology it is hard to start a new strategy. Therefore some resistance is expected. There will be shortcomings when comparing a building skin to a natural skin. Nature's skin is alive and has the ability to constantly regenerate.

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