Electives 2014

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BKAI 09/13

Topic: To what extent can biomimicry have an impact on the materials and shapes used in industrial production processes?

Title: Biomimicry in industrial building processes

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1 Introduction

When we think about the industrial production processes in the building industry, the first thing that mostly comes up is standardization of measurements, the core materials (insulation, concrete, wood, steel. etc.) and even the shapes.
Even though prefabricated elements have given us beautiful buildings and the ability to build higher and bigger in less time due to this standardization, the dole prefabricated housing projects from the 70's and 80's stay fresh in our memory. These days this template way of building is still widely applied to new student accommodation and in fast growing cities around the world. It always seems to be a battle between cost, functionality and aesthetic value.
But is this truly the case? There are numerous examples of buildings that take this standardization to the next level and succeed in creating beautiful architecture without driving the costs through the roof.
Many of the engineers and architects who design these constructions, turned to nature for their inspiration and came up with solutions by mimicking the processes and structures they found in biology.
A lot of structures that we use in the daily design process are also derivated from nature without us even thinking about it, like truss constructions, which we can find in bone structures, or flying buttresses added to churches, who have many similarities with the plank roots of trees in the rainforest, adding more stability to the main structure. We just know how to use it out of logic, because they are established after being used for ages, or because somebody else has done the research and use of it is widely accepted.
So I wonder, what else could we learn if we really turn to nature for answers and what did the engineers and architects find out who made biomimicry and bio morphism their life work.
In this elective I would like to take you on a journey throughout some inspiring buildings to investigate the bio mimicked features (processes, shapes and materials) that make these buildings unique and figure out if these features lower the cost of the building, but if they add value at the same time in the form of functionality (energy, moist regulation, air conditions,…) and aesthetics.

1.1 Definition

The term biomimicry saw the light of day in 1962 when it first appeared in literature and got more in use by material scientist in the 80's. The last 10 to 15 years it got more and more used in different fields as well, like engineering and architecture. But what does biomimicry mean? The problem you get when a word has not been around for very long is that it has not yet gotten an established meaning. For biomimetics (the study of biomimicry) professor Julian Vincent it is "the abstraction of good design from nature", but for biological science writer Janine Benyus it can be described as "the conscious emulation of nature's genius" and dictionary.com defines it as "the mimicking of life using imitation biological systems". I found a definition that suites our topic better in the book "Biomimicry in architecture" by Michael Pawlyn.

Biomimicry is "mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions".

Since we are in the realm of architecture we must make sure not to mix up biomimicry with bio morphism. Where biomimicry concentrates on the functionality, processes and systems of nature, bio morphism only looks at the aesthetics of nature, and is inspired by its shapes, colors and rhythm.

The TWA terminal at the John F Kennedy Airport in New York is a good example of how bio morphism is applied to architecture. It's hard not to see where architect Eero Saarinen got his inspiration for shape of his building. With a little bit of imagination you can almost see the whole structure take off.

2 Biomimicry in building disciplines

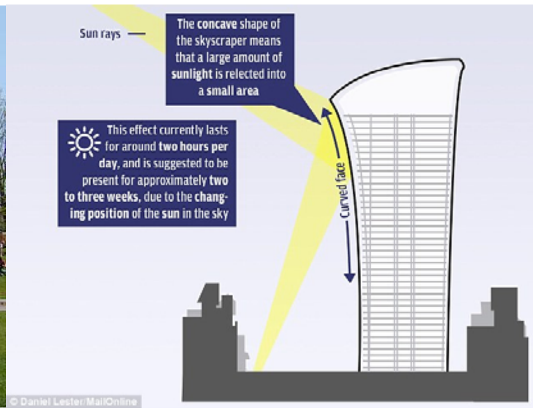
2.1 Design

Architect Ken Yeang says that biology is his greatest inspiration because nobody can invent better than nature, also stating that 80% of the impact of a building is caused by its design.

The impact a building has on its surroundings or inhabitants can vary in many ways. A beautiful building from a distance like the "Walkie-talkie" building in London can have less pleasant side effect in the streets surrounding the building. Because of its curved glass façade the building started reflecting solar beams, combining them into 1 point like a magnifying glass, scorching bicycles, parts of cars,… and became quickly dubbed as the walkie-scorchie. The very skilled and honored architect Rafael Vinoly should have learned from his mistakes by now since his Vdara tower in Las Vegas was giving guests at the pool already an unwanted sunburn. But a well-designed building isn't just pleasing for the eye, it also provides us with a good indoor climate, has nice accessibility (for wheelchair patients, but also from a public transport point of view), and does not feel out of place where between its neighboring building. It ties together the surrounding public space and bring functionality and aesthetics to it.

Aaron Betsky takes a different approach to the design of a building. In his book "Landscrapers; building with the land" he makes a difference in the architecture that clashes with its surroundings like skyscrapers, building that are put in the landscape, like a small village with the church tower in the middle, or architecture that merges with the landscape. He calls the last one geotecture, "the way in which architects are building into the earth, merging man-made form with the contours of the land". This can be made possible in many ways. If we take a look at history we will find the first drawings of men made in caves, or less a long time ago we find the amphitheaters of ancient Greece carved out of the slope of a hill. But since the introduction of the green roof we see more and more geotecture buildings being build.

As you might have noticed already, biomimicry is such a big design discipline and can have an impact on so many different levels, which is why I would like to focus mainly on the loadbearing part in this elective.



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2.2 Loadbearing

Lean thinking trough biomimicry: Less material, more design

2.2.1 Skeletons and truss constructions

The shape of a vulture's metacarpal is identical to that of a Warren truss, using struts and ties as a matrix to create structural debt between top- and bottom cords or surfaces, when needed creating multiple layers. The birds got to this structure because of evolutionary pressure to reduce its weight but at the same time increase its strength and thickness. The understanding of skeletons and how their shape can contribute to engineering and architecture has developed a lot the last 10 years, especially Claus Mattheck did a lot of research in this field. The Warren truss is a very good example of the "material is expensive, shape is cheap" saying or "the axiom of uniform stress" stating that in the locations of stress concentration material is build up until there is enough to distribute the loads, but at the same time no material remains in the unloaded places, resulting in perfect efficiency.

This principle is widely used in bridges. We must only think of a simple army bridge to recognize this structure, or even the railroad bridge here in Aalborg.

But the inspiration from nature can also come from a design point of view as I mentioned before. One of the buildings that must resemble a bird the most is the Milwaukee Art museum designed by architect Santiago Calatrava, a good example of a structure where biomimicry and bio morphism come together. The Quadracci Pavilion, build in 2001, is actually an addition to an already existing war memorial. This pavilion, part of The Milwaukee Art museum, is situated next to Lake Michigan, and Santiago took all of his inspiration for the building straight out of the surrounding. The bird like pavilion, the sailing boat like bridge and the exhibition space shaped as a wave can all be seen around the building.

The bow/wave of the exhibition space (Windhover hall) is Caltrava's interpretation of a gothic church, complete with characteristic flying buttresses, pointed arches, ribbed vaults, and a central nave topped by a 90-foot-high glass roof. The wing structures are mounted on this glass roof and they control the amount of light let into the building. Being a nice piece of engineering the 72 steels fins with a length varying from 8 to 32 meter close automatically when wind speeds rise over 37km/hour for more than 3 sec. This iconic structure shows perfectly how design, functionality and technology go hand in hand in good architecture.

Although I do think the project would not have become this ambitious without the support of the people from Milwaukee since it is paid mainly by crowdfunding. The bigger the success of the crowdfunding became, the more Calatrava could complete his design. And at this moment this is probably one of his most loved projects as well. These days Calatrava is called by some the most hated architect in the world because of his overtime, over budget prestige projects, like the World Trade Center transportation hub, the Valencia opera house or the Zubizuri Bridge in Bilbao. If the accusations are justifiable or not, it is most admirable what architecture can do and become as art form. But at the same time it is always important to keep your scope in the right perspective and don't let arrogance lead you.

2.2.3 Web structures

When we talk about web structures, we must credit German architect and engineer Frei Otto. Frei Otto dedicated his life to this way of building. He pioneered cable-net structures, founded the institute for lightweight structures and published 36 volumes on structural design principles inspired by nature where he explains in detail nature based systems from radiolaria (small protozoa with a primitive mineral skeleton) to skeletons and trees , but of course also web structures, and he shows the different possibilities in architecture.

If you think about a spiders web and try to convert it to that of a building, you encounter quite fast some difficulties on practical and engineering level. So when we talk about biomimicry we can't be blind to the obstacles it might present as well. If a string of a spider web breaks, the spider doesn't mind that much, it recycles the string and gets back to work, while for a big construction this could take days to repair, and since these cables would be under tension, it would be very dangerous if one snapped as well. At the same time spiders don't mind some deflection, and even though we accept some deflection in a tent structure, we always want to limit it as much as possible, if only for our cladding systems.

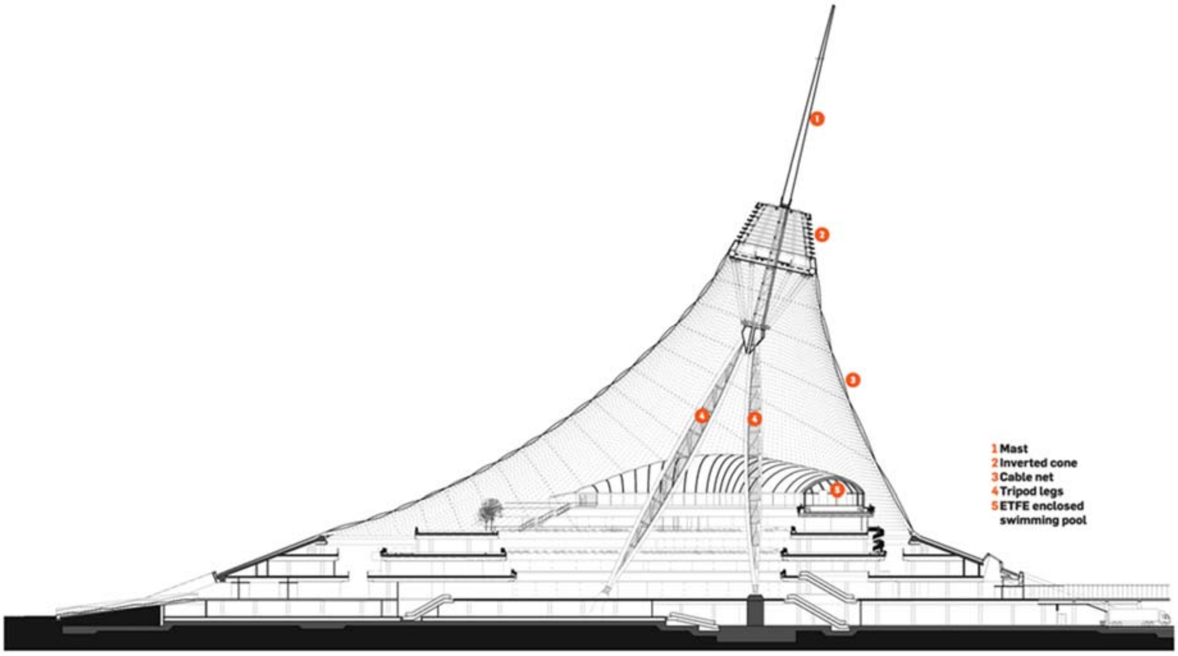
Although these problems occur, tent/ web structures have proven to be very useful and elegant structures. One of the first times Otto showed his tent constructions was on the Expo of 1967 in Montreal where he build the pavilion for West-Germany. The pavilion displays a lightweight roof structure created by cable net as tension structure. The net/web is hung up between vertically standing masts.

When Fritz Auzer won the competition to design the Olympic park and stadium in Munchen he used the German Alps and Otto's pavilion as inspiration. Since it was such a young design field, it was quite normal that Frei Otto was added to the design team as soon as the first problems aroused. Just like the German pavilion in Montreal they used a steel cable net for the roof construction of the stadium strung between the different masts. All together the cable matrix roof spans an area of 74 800 m² and is covered with Plexiglas. During summer you can even plan excursions on this huge tent.

Since the summer Olympics in Munchen the tent constructions have come a long way. The most recent giant project was definitely made by Architect Norman Foster. He and his team are building the biggest and most ambitious tent projects in the world at this moment like the Khan Shatyr in Astana, the capital of Kazakhstan. They brought the tent to the 21st century, making it a climatic envelope, hung up on a tubular steel tripod structure, protecting its indoor climate with a 3 layer ETFE –foil cushion of 3.5x30meter size (in the next chapter more about ETFE-foil). The cushions are placed in a net of radial and circumferential steel cables like the tents of Frei Otto.

The original idea of tents with a steel cable matrix might have had spider webs as main inspiration, but in the case of the Khan Shatyr it's hard to look past the influence the nomadic life of the Kazakh ancestors had on this project. They understood the inhospitable climate of the central Asian steppe with temperatures varying from -35°C in winter to +35°C in summer. They have had their battle with it for many centuries in their tradition tents. Now they have an additional home in this 150 meter high structure based on an elliptic foundation of 200x195 meter.

When such a big tent is placed into a climate with extreme temperature differences a good ventilation system is not an unwanted luxury. To reach their indoor target temperatures of +14°C during winter and +29°C in summer they made use of different types of heating and ventilation. For starters you have the solar radiation that is let in by the ETFE- foil and that warms up the inside in a natural way. But this is not enough and could have an adverse effect during summer. So low-level jets were installed to direct cool the air entering the space. Additional to that vents at the apex of the building induce natural stack-effect (or chimney effect) ventilation. Because the extreme cold temperatures in winter the design team projected a warm air current on the inner layer of the ETFE foil. This way they prevented downdraft, but even better prevented ice forming on the inside of the tent.

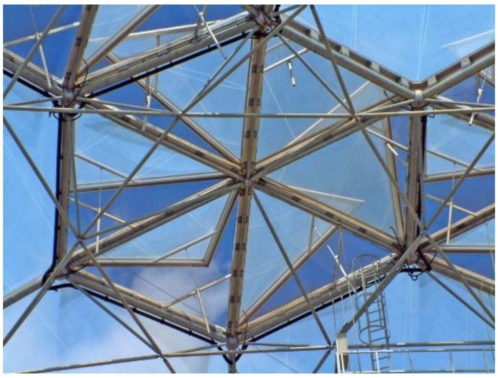


At this moment the Khan Shatyr still is the biggest web structure in the world. But that will change once the construction of the biggest man maid structure in the world begins in Moscow. Also a project designed by Foster and partners, the "Crystal Island" will truly be of monumental scale (If they ever start building…)

2.2.4 Domes

Geodic dome

The geodic dome can be seen as a perfect ball like shape existing out of a frame made of a hex-tri-hex structure. This is a structure (as can be presumed by the name) consisting of small hexagons or pentagons which on their turn are subdivided into smaller triangles. Richard Buckminster Fuller pioneered this way of building after doing numerous amounts of research on pollen grains and carbon molecules. He even got a carbon molecule named after hem called the "Buckminster Fullerene". But in the geodic dome you can also find inspiration coming from beehives and the tube/node structure of bamboo can be seen in the way the joints are



put together. The geodic dome still stands symbol for the future and innovation, that's why every science or astrology museum in the world has one.

A different contribution of the geodic dome in a much larger scale can be found in the biomes of the Eden project in Cornwall, England. At the start of project architects from around the world where called to create the biggest greenhouse in the world. But the location of the greenhouse did not make the project any easier. Situated above a 90 meter deep china-clay pit of a few 100 meters across and to make matters worse, the pit was still being exploited at the moment of the brief, so there was no certainty of its eventual size. But the architects and students from Grimshaw (from founder Nicolas Grimshaw) accepted the challenge knowing that "the most difficult challenges often hold the potential for the most inventive solutions".

One of the challenges was to find the wright place on the site for their greenhouse to be build. Surprisingly the clay pit helped in their favor in this case, providing the right amount of shelter for microclimates to exist. The designers also decided to orient their greenhouse on the south facing slopes so passive solar radiation would be maximized. Another problem was the unevenly divided proportions of the pit and the differences in height because of the hilled environment in combination with the clay basin, until one of the students thought of a bubble like structure that would be guided by the landscape instead of clashing with it. They decide to make a series of these bubble structure, much like a necklace. This way they could adjust their design according to the pit size at that given moment, keep in consideration the height of the landscape, but also the height of the plants and trees that should inhabit the biomes.

One of the last challenges was to find the lightest possible structure. And that's how they ended up with the hex-tri-hex structure of Buckminster. Another reasons being that it's a self-supporting system, so no support is needed inside the dome when completed and the plants can't interfere with the integrate of the construction. Once they decided on the structure they explored different solutions in how to maximize the size of the hexagons, so the maximum amount of sunlight could be let in the greenhouse. A steel frame was a logic solution, since it's very strong but at the same time quite light compared to other materials. But the bigger the hexagons got in the design, the more it became clear that glass would not be able to support such a big span. Glass had very good qualities when it comes to solar penetration, but it also becomes heavy very fast and the unit size is rather limited. But they found a solution in a triple layer ETFE- film. ETFE-foil (ethylene tetrafluorethylene) is a high performance UV-transparent polymer that can be made into a lightweight cladding element by sealing the edges around the perimeter of the three layers and inflating it for stiffness. This way they created large cushions that provide insulation for the greenhouses and let sunlight through at the same time. By using ETFE-foil the architects and engineers were able to reduce the weight to 1 percent of the weight it would have had using glass and they reached spans up to 9 meter what else ways would have never been possible.

This process of design refinement worked as a cascade effect throughout the building. Bigger cushions resulted in less steel being used for the substructure, which ended up letting more sunlight in the building, this way they have to use less heating in the winter periods. But because of the bubble design there was less excavations needed to start the building process. So in the end they used a fraction of the resources compared to the conventional way of building and they manage to reduce the cost to 1/3 of the normal rate for a greenhouse of this size.

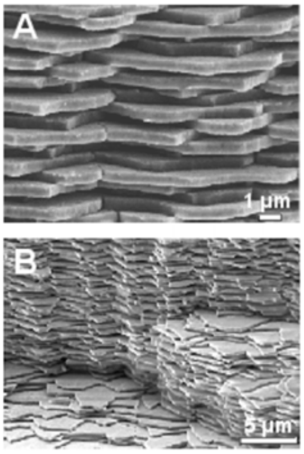
They did not just create the world's biggest greenhouse, but left a landmark in the hilly countryside of Cornwall. In its first year after opening alone it attracted 1.956 million visitors and it's currently the second most visited destination in Great Britain besides London.

Ferro-cemento

Another remarkable example of stiffness is provided by the giant Amazon water lily and is adapted successfully to architecture by structural engineer Pier-Luigi Nervi in all sorts of roof constructions. One of these examples you can find in the Palazzetto dello Sport, build in 1957 for the summer Olympics of 1960 in Rome.

During his Life Nervi invented some of the building processes and elements we use today: prefabrication of elements and reinforced concrete, both are implemented on great scale in this building.

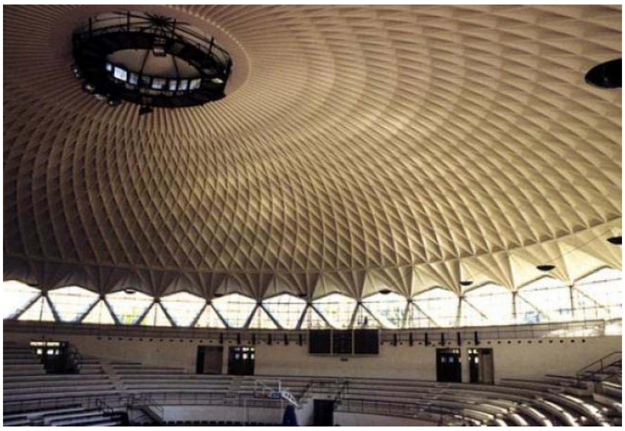
The problem is that we stop our creativity there were we only use the prefabricated elements that are reached out to us. And this is where Pier-Luigi Nervi takes construction a step further.



In Nervi's Palazzetto dello Sport reinforced concrete wasn't only used in the conventional way we are working with this material (as TTS beams, solid slabs,…), but he created his own "ferro-cemento", a thin, flexible, elastic but very strong piece of engineering. This material consisted of multiple layers of fine steel mesh sprayed with cement mortar within a mold to create a smooth surface, mimicking the way a seashell is build up out of multiple layers of aragonite (a kind of calcium carbonate) held together by a flexible polymer. This way there was no additional finishing required and the elements could be prefabricated with a thickness of less than 40 mm. The elements in their turn were welded together at the protruding steel bars from each adjacent unit and grouted to create a former for the in-situ concrete that unified the whole structure.

The whole nerve system, which is still visible, follows the main stress of the entire roof construction and provides the building on his turn with excellent acoustics.

When finished the concrete rib supported dome spanned a diameter of 61 meter, itself consisting of 1620 prefabricated elements that were braced by flying buttresses. The dome was erected in 40 days.



The beauty of constructing in this way is in achieving efficiency through complexity without adding excessive cost. For Nervi the tool he could use for his building was reinforced concrete “the very fact of not having at its origin a form of its own… permits it to adapt itself to any form and constitute resisting organisms” he said and “concrete is a living creature which can adapt itself to any form, need or stress”.

And maybe sometimes we should think about it like that as well.

3 Conclusion

During the research for this elective I have encountered many ways biomimicry has been used direct or indirect as inspiration. This makes me believe that in the near future we will see an even greater use of these qualities within the building industry in large and small scale in combination with traditional building techniques.

The green roof is already widely used as a thermal regulator, many types of mix mechanical/natural or just natural ventilation are integrated in the design process and we are looking more and more to cradle to cradle solutions for the building components that we use. All these things are signs that there is a change going on within the industry. And these signs are very hopeful. I would like to do more research in these systems in my future electives.

But if we really want to reduce our amount of waste and also the amount of materials used in general we will have to go even further. I believe (as many of the examples given above) biomimicry in addition to 3D modeling and printing can reduce the cost and materials with a factor between 1/10 and 1/100 depending on the given project and also with a minimum amount of waste (go for zero) at the end of the buildings lifecycle.

Past semester we have been learning a lot about lean thinking and Blue Ocean companies. After this elective I have learned there is a huge gap in the market for companies that bases its innovations on biomimicry and fundamental sustainable building. Together with biomimicry the building of the future will not only be sustainable but will have an active impact on its surroundings, being the provider of fresh air, energy and at the same these buildings will be integrated with the public space.

4 case studies

Eden project by Grimshaw, Cornwall, UK, 2001

Khan Shatyr by Norman Foster and partners, Astana, Kazachstan, 2010

Milwaukee Art museum by Santiogo Calatrava, Milwaukee, USA, 2001

Olympic stadium of Munchen by Frei Otto and Fritz Auzer, Munchen, Germany, 1972

Palazzetto dello sport by Pier-luigi Nervi, Rome, Italy, 1957

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