Biomimicry in Architecture
Biomimicry in Architecture
Come forth into the light of things,
Let Nature be your teacher.

-William Wordsworth

Enough of Science and of Art;
Close up those barren leaves;
Come forth, and bring with you a heart
That watches and receives.

-William Wordsworth
First and foremost, thank you to professor Toni Kotnik for your insights and advice. Thank you also to professor Jenni Reuter for your support and compassion. Both of you have made this process significantly more enjoyable than it otherwise might have been.

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Tie on ollut pitkä ja (jalo)kivinen, eikä syytä.

Satu Niemi
Helsinki, May 2017
Tämä työ tarjoaa yhden määritelmän ja tulkinnan biomimiikasta (biomimicry), sekä ehdotuksia siitä, miten sitä voisi käyttää arkkitehtuurissa. Työ koostuu kirjallisuuslukemisesta ja esimerkkejä analyyseista analysista. Esimerkkikohteet on valittu sen perusteella, miten niissä on käytetty kasvien sopeutumisstrategioita malleina ympäristöön reagoivan rakennuksen vaipan suunnittelussa.

Tässä työssä biomimiikkia määritellään sellaiseksi analyyttiseksi luonnon imitoimiseksi, jossa luonnossa esiintyvistä prosesseista, materiaaleista, rakenteista ja systeemeistä saatuja oppia käytetään ihmisten suunnittelumissä, ja apua tekniisiin ja ideologisiiin ratkaisuihin kestävän kehityksen mukaisella tavalla. Biomimiikkia on arkkitehtuurin tutkimuksen ja perustelunäkökulmaa, ja sen käyttöä on laajennettu muualta tutkimukselta. Bioanalogiat ja -ratkaisut on luonnon sekä luonnonmukaisuuden uudessa ulkoasussa esitettyä. Biomimiikkaviestorakennuksissa käytössä on dynaamisesti ja kestävästi kehitettävä ja kehitettävä.

Työn toisessa osassa analysoitiin biomimetian määrittely, ja esimerkkikohteen esitys, mitä sen sisältää ja miten se voi olla käytettävissä arkkitehtuurissa. Esimerkkikohteita on valittu sen perusteella, miten niissä on käytetty kasvien sopeutumisstrategioita ja niissä on käytetty kasvien sopeutumisstrategioita, jotka ovat kestävästi ja kestävästi kehitettävissä.

Lopuksi esitetään tiivistelmänä biomimiikka määritelmä ja potenriali arkkitehtuurissa, sekä kestävien ratkaisujen vaikutus ympäristöön ja ympäristöön kunnioittavissa arkkitehtuurissa. Työ koostuu kolmesta osasta: biomimetiikasta, biomimeticoinen arkkitehtuuri ja biomimeticoinen suunnittelu, sekä biomimeticoinen arkkitehtuuri ja biomimeticoinen suunnittelu. Työ on analysoitu ja esitetty tiivistelmänä biomimicry- ja biomimetics-aiheessa.

**Avainsanat:** arkkitehtuuri, biomimiikka, biomimetiikka, biomimeettinen suunnittelu, biomimicry, biomimetics, biomimeettinen suunnittelu.
This thesis provides one definition and interpretation of biomimicry and a review on how biomimicry could be used in architecture. This is done through a literary study and the analysis of chosen case examples. The case examples showcase the use of biomimicry in the design of building envelope solutions that respond to the changes in the environment by emulating different adaptive strategies found in plants.

The thesis is in three parts: Defining biomimicry, Designing with biomimicry, and Case studies. In addition to the three parts, a summary with final thoughts will be given at the end. The first part of this thesis gives a brief overview of natural analogy in the history of Western architecture and design. Two types of sub-categories in the natural analogy are identified: the organic analogy and the biological analogy. The biological analogy can be further divided into anatomical, classificatory, ecological, evolutionary, and growth analogies in accordance with the way parallels are drawn from natural phenomena and the concepts of biology. Developments in architectural styles are illustrated with examples from architecture.

In this thesis, biomimicry is defined as mimicking nature by understanding and learning from the processes, materials, structures and systems found in nature, and utilising the results in comparable man-made designs, applications, methods or procedures to achieve more sustainable solutions to any given problem.

Biomimetics is a direct predecessor of architectural biomimicry, and the terms are sometimes used interchangeably. In this thesis, the use of the term biomimicry denotes a broader scope of ventures than the ‘engineerability’ of biomimetics, with environmental and societal aspects. A biomimicry-driven approach to design includes the incorporation of biomimetic solutions to an array of problems, often technical. These solutions should enhance the environmental sustainability of the design and provide positive feedback to the systems the design is a part of. The problems to be solved with biomimicry at large need not be engineering problems, but in relation with architecture they most often are.

The second part of this thesis further examines the concept of biomimicry in architecture and its definition in the contemporary context and use of the word. In addition, an overview of how biomimicry can be used to tackle challenges in architecture is given. Furthermore, the value and relevancy of biomimicry is discussed along with criticism towards the subject. Based on different approaches to a biomimetic design process found in literature, the author formulates their own take on the process, which is then used as an aid in the analysis of case studies.

The third part of this thesis is the analysis of case studies according to the context laid out in the first and second parts of the thesis. The cases are each studied based on the type of natural analogy used, how biomimicry presents itself in the design process, and what the relationship between biomimicry and their architectural expression is.

Finally, as a conclusion to the work, the definition and potential of biomimicry as a design approach in architecture is summarised, along with possible shortcomings of the approach and some speculations about the future of biomimicry in architecture.

Keywords: architecture, biomimicry, biomimetics, biomimetic design, biomimic design
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The idea for this thesis has been brewing in my mind ever since I was introduced to the world of biomimicry by architect Anna Maria Orru at Kungliga Tekniska Hogskolan in 2012, but the process of finding a path to follow has been a long one. My interest and curiosity towards biomimetics and biomimicry as new way of thinking and approaching design was further fuelled by architect Michael Pawlyn’s visiting lectures at Aalto University in 2013. I was inspired by the message they delivered: there is a way of working in which the architect does not impose their design on to the environment, but rather humbly studies the surrounding world and searches for ways to learn from it and complement it. I was most struck by the lack of the architect’s often overpowering ego in the biomimicry process and the infinite world of inspiration and information available in nature to whoever cares to look for it.

This work was originally intended as a credo to biomimicry, which would convince anyone reading it that biomimicry is the future of design. I wanted to formulate a biomimicry process I could carry on into my own architecture practice. However, as I delved deeper into the subject, the task of making arguments for biomimicry transformed into a journey of exploration. What exactly is biomimicry? Why is it important? Can it be truly useful in architecture? How to reconcile biomimetic engineering with ambitions for architectural expression? These are some of the questions I have asked myself while writing this work, and though some have been answered, I will keep re-asking them in my own practice of architecture.

It took five years from my first introduction to biomimicry for the idea of a thesis to mature into a finished work. In this time my conception of biomimicry has been in constant flux. At first, as in any new field of study, my approach was defined by enthusiasm unbridled by any criticism towards the subject. As I learned more, I started to see a more complex picture of biomimicry as an approach that is not perfect but still worth pursuing. I know now that biomimicry is not a magical tool that automatically leads to good design. As I started writing this thesis a little over a year ago, I learned the danger of a little knowledge – I thought I knew what biomimicry was, but was soon challenged to justify my view. This work has helped me clarify my view, but made me all the more aware of the fact that it is only one of countless other interpretations.

In the end, I set out to explore two things in this thesis: first, to understand what biomimicry actually means in architecture; and second, to find out for myself what kind of relevance it might have beyond technical and material advancements. I had hoped that this work would help me not only find out what biomimicry is, but also to consider how relevant it can be and how to use it as an architect. In these aspects I have learned what I set out to do. As for formulating my own design process, the Biomimicry Design Cycle presented in this work will definitely prove useful in my future work, and I hope to develop the thoughts on it further.

To you reading this, thank you for sharing my interest. I hope this work can pass on to you some of the curiosity towards biomimicry I have received from architects far better initiated than I am.
Analogy refers to the concordance of functions. In biology, analogue refers to a part or organ in one animal that has the same function as another part or organ in a different animal, e.g. the wings of insects, birds or bats. In ethnology this means separate people finding similar solutions to similar problems independently, without the spread of ideas through trade or migration.

Architektur-Bionik translates directly to architecture bionics, but has been in this thesis translated to architectural biomimetics to better convey the meaning of the term.

Bau-Bionik translates directly to building bionics, but has been in this thesis translated to building biomimetics to better convey the meaning of the term.

Biomimicry, from Ancient Greek: βίος (bios), life, and μίμησις (mimesis), imitation, from μιμεῖσθαι (mimeisthai), to imitate, from μῖμος (mimos), actor.

Biomimetics, a portmanteau of biology and technology.

Bionics is a branch of engineering that has systematised the study of the biological mechanisms that promise to have practical applicability in man-made devices. The term bears a slightly different meaning that the German word Bionik, which is roughly equivalent in meaning to biomimetics in English.

Bioutilisation entails harvesting a product or producer, e.g. cutting wood for floors, wildcrafting medicinal plants. It is also distinctly different from bio-assisted technologies, which involve domesticating an organism to accomplish a function, e.g., bacterial purification of water, cows bred to produce milk.

Dynamic adaptive mechanisms describe how plants respond to external stimuli through movement called tropisms or nastic movements. By definition, the difference between these two types of movements depends on whether the motion or response is dependent on the direction or position of the stimulus or trigger. In this thesis, the definition of the term dynamic adaptive mechanism is broadened to include analogous adaptive mechanisms (mechanisms that rely on the movement of parts in response to external stimuli) in other organisms and in architecture.

Homeostasis is the tendency of a system, especially the physiological system of higher animals, to maintain internal stability by means of the coordinated response of its parts to any situation that would disturb its normal condition or function.

Homology refers to the concordance of structure. In biology, homologue refers to the same organ in different animals under every variety of form and function e.g. human arm and front leg in quadrupeds. In ethnology this means cultural diffusion, spread of ideas through trade and migration.

Static adaptive strategies describe the ways in which plants have adapted to their environment through their physiological or structural properties. In this thesis the term is used to refer to analogous strategies in other organisms, such as the self-cleaning Lotus effect of the taro plant leaf (Colocasia esculenta), or the massing of a building volume in such a way as to maximise self-shading.
Biomimicry in architecture – what does it actually mean? Biomimicry is a term used to mean inspiration taken from nature in different fields ranging from design and engineering to medicine. Each field uses a slightly different interpretation of biomimicry suited to its specific conditions. This thesis will provide a definition and interpretation of biomimicry that is specifically attuned to the field of architecture, and a review on how biomimicry could be used in architectural design. This is done through a literary study and an analysis of illustrative case examples.

The thesis is in three parts: Defining biomimicry, Designing with biomimicry, and Case studies. The first part will focus on placing biomimicry in a historical and ideological context by giving a brief overview of natural analogy in the history of Western architecture and design. Biomimicry is by its most literal definition the mimicking of nature, and to help understand what that means, one needs to understand different ways nature can and has been mimicked. Natural analogy in design will be further examined by dividing it into two different strands: the organic analogy and the biological analogy. The biological analogy is composed of anatomical, classificatory, ecological evolutionary and growth analogies in accordance with the way parallels are drawn from natural phenomena and the concepts of biology. After the context of natural analogy has been laid out, developments in architectural styles and ideologies will be mapped out to form an overview of where biomimicry lands in this historical and ideological context. Examples from architecture help illustrate the different types of analogies.

The first part of this thesis will also discuss the relationship between biomimicry, biomimetics, and bionics. The interpretation of these terms depends on the language of the discussion as well as the field of research they are used in. Biomimetics is a direct predecessor of architectural biomimicry, and the terms are sometimes used interchangeably in discussion and literature. Biomimetics has gained momentum and interest especially in the fields of material engineering since the coinage of the term by American inventor, engineer, and Biophysicist Otto Schmitt in the 1950s. The term is a portmanteau of the words biology and technology, and has a wider meaning of applying natural principles and systems to engineering than bionics, which has a focus on medical and robotic applications. In architecture, a biomimetic approach has influenced the works of numerous architects and engineers including Buckminster Fuller and Frei Otto. In a German-speaking context, the term Bau-Bionik has been used to describe concepts that in an English-speaking context fall under the umbrella of building biomimetics – biomimetic solutions designed specifically for the needs of building and structural engineering, architecture, and design. Architect J.S. Lebedew uses the term Architektur-Bionik in relation to biomimetics for architecture in his 1983 book Architektur und Bionik, which has been influential in the field of biomimetic especially in German-speaking countries and former Eastern bloc countries in Europe. In this thesis, Architektur-Bionik will be translated into architectural biomimetics, bearing roughly the same meaning as building biomimetics.

Biomimicry is in this thesis defined as mimicking nature by understanding and learning from the processes, materials, structures and systems found in nature, and utilising the results in comparable man-made designs, applications, methods or procedures to achieve more sustainable solutions to any given problem. Sustainability is the key element separating biomimicry from biomimetics. The use of the term biomimicry denotes a broader scope of ventures than the ‘engineerability’ of biomimetics, including a concern for environmental and societal aspects. American natural sciences writer Janine Benyus has promoted biomimicry as a tool for sustainable and resilient
design since the late 1990s, and her view of ‘nature as measure’ of what is good design has attracted interest in architects ever since. A biomimicry-driven approach to design includes the incorporation of biomimetic solutions to an array of problems, often technical. These solutions should enhance the environmental sustainability of the design and provide positive feedback to the systems the design is a part of.

The second part of this thesis will further examine the concept of biomimicry in architecture and its definition in the contemporary context and use of the word. The chapters in the second part will give an overview of how biomimicry can be used to tackle challenges in architecture: why, where, and how could biomimicry be used in architecture? Furthermore, the value and relevancy of biomimicry will be discussed along with criticism towards the subject. What is successful biomimicry in architecture, and how do the technical solutions relate to the artistic merits and architectural expression of a design? The most relevant of these questions for the architect is ‘how’ – to aid in this quest, the Biomimicry Design Cycle will be proposed. The Biomimicry Design Cycle illustrates the phases of a biomimicry approach to an architectural design task, and is intended as a tool to help those seeking insights into incorporating biomimicry in their own design.

The third part of this thesis consists of the analysis of case studies within the context laid out in the first and second part of the thesis. The case examples have been chosen to showcase the use of biomimicry in the design of building envelope solutions that respond to the changes in the environment by emulating different adaptive strategies of plants. The cases will each be studied based on the type of natural analogy used, how biomimicry presents itself in the design process, and what the relationship between biomimicry and the architectural expression of each design is. The cases studied have been chosen to illustrate a certain line of inquiry, in that they all respond to similar challenges in design by drawing analogies from a similar pool of natural precedents, but with very different end results. This is to illustrate how even a similar approach to a design challenge can lead to a multitude of designs and architectural expressions, each as valid as the other. Biomimicry does not dictate the result of the design, but it is a tool for the architect to choose a path to travel.

Finally, as a conclusion to the work, the definition and potential of biomimicry as a design approach in architecture will be summarised, along with possible shortcomings of the approach.
Defining Biomimicry
To understand the concept of biomimicry, it is essential to get an overview of where it fits into the world of natural analogy in architecture and design. The following chapters will lay out the larger conceptual and historical framework of natural analogy and expand on the concepts and terms relating to it.

First, what does the term *natural* mean in this context? In this thesis it is used to describe anything pertaining to nature, and things relating to and studied by natural sciences. This includes biology and the physical sciences: physics, astronomy, chemistry, and Earth sciences. The definition of the term is made so as not to exclude natural phenomena that do not fall within the organic realm, e.g. weather phenomena or erosion. To make a further distinction, the term *organic* is in this thesis used in reference to living entities, excluding the *inorganic*, such as weather phenomena. The term *biological* is used to distinguish between the natural world and the science of studying it. Biology as a science is concerned with the study of life and living organisms, including their structure, function, growth, evolution, distribution, identification and taxonomy, and biological analogies draw from the same aspects.

Nature, however, is more than just the quantifiable aspects of it. Susannah Hagan makes an excellent notion in her book *Taking Shape* (2001), that the word ‘nature’ means two different aspects: a material reality and a cultural construct. The two exist in parallel, but can never mean the same thing. The material reality exists as itself, but our cultural construct of nature is subject to change and interpretation. The cultural construct of nature is what shapes our relationship towards the quantifiable nature, and dictates the analogies we draw from it. This should be kept in mind when looking at the way natural analogies have influenced and shaped architecture throughout history.

As long as humans have built shelter from the natural forces, they have looked to their surrounding nature for learning and inspiration. Imitation runs throughout the history of architecture. How this imitation has presented itself, or what aspect of nature has been imitated or mimicked, is a matter of interest in the following chapters. In his book *Nature and Architecture* (2000) Paolo Portoghesi goes so far as to argue, somewhat misguidedly, that from a certain viewpoint architecture itself becomes part of nature, just like the coral reefs or shells, or the dams built by beavers. This argument is challenged on closer inspection: coral reefs and shells are unconscious productions of the organisms’ anatomy, whereas beaver dams and human houses are not. The fallacy of Portoghesi’s argument will be further argued in chapter 4.3, *The ecological analogy*.

It is dangerously easy to make generalized claims about the relationship of humans to nature, or the psychological meaning of nature to humans. These interpretations are often subjective and intuitive, lacking definitive knowledge of the workings of the human species as a part of the natural world. This thesis claims no such knowledge, and so will refrain from making arguments about the meaning of nature for the human psychology. Excluding the describing of historical examples, the meaning of natural analogies for architecture will in this thesis be discussed in utilitarian terms. Some broad notes should be given about the relationship between human and nature, however. Our modern relationship with nature, one characterised by human dominance, is not a given. The relationship, or rather our interpretation of it, is in constant fluctuation. It has ranged from the ideal of the inherent goodness of nature and the organic as something divine, to that of trying to understand the natural laws that govern it, and to that of imposing our dominance on nature and exploiting it. This fluctuation in attitude will be seen in the chapters detailing different types of analogies. In recent
times there have been some signs of a shift towards a new form of relationship, where humans as a species could find a balance with nature: stop fighting against its forces and instead work with them. The surge of interest in biomimicry is one of those signs. Concerning not only architecture and design, natural analogies have developed with and affected all aspects of human societies throughout history. We as a species are an inseparable part of the material nature, and enmeshed in our cultural construct of it. The relationship of architecture and nature can be seen in correlation with the way human societies have seen nature throughout history: first as something divine and savage, then as something to control and exploit, and perhaps finally as something to learn from and find one’s place in.

The field of analogy between nature and architecture does not lend itself to easy navigation. Every architectural theory or style has some relationship with the notion of nature: be it embracing, rejection, mimicry or plain indifference. Concepts and ideologies overlap each other, branch out in new directions and come back together. In architecture, some analogies draw inspiration from nature in a very literal and latent sense, others try to explain or categorize existing buildings; others yet strive to create homologies through analysis and implementation. The built world is subject to constant interpretation and reinterpretation by successive generations, and other people than the designers themselves read ideologies into buildings and place labels on architectural styles post hoc.

According to Portoghesi, the type of imitation that characterises architecture, as far as nature is concerned, is essentially ‘symbolic imitation’. This is true with regard to much of the history of architecture. However, with the development of natural sciences and biology, the imitation has shifted more to the functional aspects of nature. That said, the imitation is still made through analogies and mimicry, which requires an abstraction and can possibly include the designer’s unconscious symbolic interpretation. The analogies between architecture and nature illustrate the overlap in the advancement of biological research and earth sciences, and the simultaneous change in the social climate and its effect on architecture. Scientific advancements have brought new and deeper ways of understanding natural phenomena, and have subsequently also brought new ways of interpreting biological examples in design. Hagan puts this development into words quite eloquently:

“As our powers of observation have improved through improvements in the instruments used to do the observing – the telescope, the microscope, the computer – so we have seen more and differently, and our view of nature has changed accordingly. This has caused us to review our position within that nature, and, eventually, the architecture that expresses that position.”

A distinction should be made here between analogies and homologies. In biology, analogue refers to a part or organ in one animal that has the same function as another part or organ in a different animal: e.g. wings of insects, birds or bats. In ethology, this means separate people finding similar solutions to similar problems independently. Homologue refers to the same organ in different animals under every variety of form and function: e.g. human arm and front leg in quadrupeds. In ethnology, this means cultural diffusion i.e. the spread of ideas through trade and migration. Portoghesi clarifies that for living creatures the processes of analogy based on the concordance of functions, and of homology, based on the concordance of structure, are reflected in architecture that is dominated by typological processes, the growth of artificial structures and, on a larger scale, the birth and growth of the
urban fabric. This manifests itself as a correspondence between structures based on a common original form, and as relationships that obey a common law.

The following chapters and the attached chart (figure 1), inspired by Charles Jencks’s Evolutionary Tree diagrams, is an attempt to map out the different types of analogies and resultant design approaches in relation to each other and the historical timeline. The basic division of analogies into organic and biological analogies is based on Philip Steadman’s excellent book The Evolution of Designs: Biological analogy in architecture and the applied arts (2008). The focus in this work is on Western architectural and ideological history. Not every possible architectural style will be represented; rather those that are specifically characterised through their analogy with nature. Due to the overlapping and sometimes muddled nature of the subject, the presented interrelations of styles and ideas are not always clear and can be subject to other interpretations. This is not meant to be a definitive or exhaustive overview of every Western theory and style of architecture and their relationship to nature, but rather a map pointing to the direction of biomimicry, so it can be further examined.

The concepts and ideologies on the map have been organized in relation to different types of analogy: the organic analogy as the basis of all the other analogies; the biological analogy further divided into anatomical, classificatory, ecological, growth, and evolutionary analogies. To understand these relationships, it is first imperative to go through the underlying principles of these analogies. This will be done in chapters 3 and 4. Brief introductions of the presented design approaches will be given only after that in chapter 5, as structuring them strictly according to one type of analogy each would be incorrect, and too simplistic a manner to present such an interconnected subject. The focus is largely on developments from the 18th century onwards, as new scientific methods and innovations and the emergence of biology as a modern science have provided for a shift from vitalist ideals and largely symbolic analogies to those of a more functional approach.

In the chart, the names of philosophers, scientists, writers and architects alike have been placed chronologically, and in connection with a certain line of analogy or theory, to illustrate their direct impact on it. For example, though Georges Cuvier and Jean-Baptiste Lamarck were both scientists with wide-ranging impacts on biology and the life sciences, their names are placed alongside the anatomical and evolutionary analogies respectively, as their work in these fields have been especially relevant and interesting to the field of design.
Natural analogy in architecture

Organic analogy

Biological analogy

Classificatory analogy

Ecological analogy

Evolutionary analogy

Comparative analogy

Ontological analogy

Synthetic interpretation

Classical architecture

Architectural Revival

Neo-Classical architecture

Gothic architecture

Gothic Revival

Renaissance architecture

Classical architecture

Man of the Vitruvian Man

Functional interpretation

'Animal Architecture'

Metabolism

Structuralism

The future
The organic analogy takes nature as a model for wholeness, coherence, and ‘natural’ beauty in the classical sense. This means the idea that there is an inherent quality of goodness in nature that should be emulated and, if possible, recreated in the creations of man. Since ancient Greece, critics and philosophers alike have looked to natural organisms as perfect models of the harmonious balance and proportion between the parts of a design. It is this balance and relationship between the parts that is synonymous with the classical ideal of beauty.8

Historically, there has been a transition between two different views of the origin of and reason behind this beauty and order. Hagan describes these as the ‘top-down’ model and the ‘bottom-up’ model. The ‘top-down’ model is religious, and sees the order of nature flowing from one divine source down into the complex and then to the simplest single-cell organisms. The ‘bottom-up’ model is Darwinian and non-teleological: instead from a divine purpose for organisms, the beauty and order arises from the interconnectedness and mutual dependence of single-cell organisms evolving to more complex life forms.9 The difference in these models is apparent in the way humans’ relationship with nature has shifted in cultures in sync with the shift from a religious to a secular society. In a contemporary context there is a division to be found as well. First, the unreconstructed modernist view, in which nature is viewed as a source of raw materials and instrumental knowledge; and second, the environmental model, in which nature is viewed as an array of interrelated and complex systems in which humans are included and upon which they are dependant. Hagan goes on to argue that since the development of complexity theory in the 1960s, the two views have united in a new way: in neither can the distinction between 'nature' and 'culture' be made with the same conviction as historically has been the case.10

In this thesis the organic analogy is used as an umbrella term for all types of inspiration taken from nature, from the very literal copying to the most symbolic interpretation: the notion of the organic is discussed both in a classical sense and in a more loose context mimicking organic morphology. The latter context is not necessarily so concerned with the wholeness and coherence of nature, but might take on an eclectic or even whimsical attitude towards its role model, as some examples of biomorphic and zoomorphic architecture demonstrate. Although the term organic encompasses almost all kinds of natural analogy, it can be taken to describe specifically two strands of architecture with considerably different views, which will be discussed later: organic architecture and 'new' organic architecture. It is surprising that the difference between these approaches is so different despite the proximity suggested by their names. According to Steadman, the organic analogy has two distinct kinds of interpretation, one to do with visual appearance or composition, the other to functional.11 The categorisation into two approaches, however, leaves out an array of symbolic interpretations of the organic. That is, there is a multitude of examples in architecture, where the beauty of the organic has been taken at its face value and then reinterpreted in design without any regard as to what constitutes that beauty. In the attached chart, the organic analogy been thus divided into three different interpretations: the symbolic, the compositional, and the functional. These three types of interpretations are not mutually exclusive, but in most cases emphasis is clearly on one approach on the cost of the others.

The symbolic interpretation of the analogy refers here to instances where a model from nature has been mimicked to evoke a feeling of nature, but without any special regard to the notion of the organic composition in the classical sense. An example
of this can be seen in decorations that take their form from nature, or zoomorphic architecture with a very literal mimicking of natural morphology.

The compositional take on organic analogy emphasises the qualities of wholeness, of integrity, and of a unity of structure such that no part may be removed without damaging the whole. These concepts are central to the Aristotelian view of both the natural world and works of art. Both Plato and Aristotle required that any literary work should have an ‘organic’ form, that it should be more than an aggregation of its parts, and this same principle was advocated by English poet and philosopher Coleridge and the early 19th century German Romantics Goethe, Schlegel and Schelling – Steadman argues that their influence can be seen in the works of American architects in the end of the century. For Aristotle, each part was essential to the whole, not only compositionally, but also functionally: “In some way the body exists for the soul, and the parts of the body for those functions to which they are naturally adapted.” The compositional aspect of the analogy has also been expressed in the attempts to codify mathematical laws of harmony in numerical and geometrical systems. This has had influence in Renaissance systems of architectural proportion (figure 2); especially the human body has served as a role model for the proportional harmony that should be achieved in architectural works. The idea was already put forward by Vitruvius, and continued by other Renaissance commentators. Later Le Corbusier built upon the theme in his Modulor system based on human measurements.

The functional interpretation of the analogy forms a part of the more general aesthetics of functionalism, the equation of the beautiful with the useful – an artefact that is well designed and fits its purpose should be seen as beautiful through this recognition of beauty. This idea can also be traced back to Aristotle and his view of the beauty of animals: our perception of beauty comes from the rational appreciation of the structure of their parts and the functions of their organs. In functionalist aesthetics, this tradition was later divided into two parallel strands: one looking towards nature and the other to the works of mechanical and civil engineering. These ‘biological’ and ‘mechanical’ analogies, despite their differences in role models, are both based on the appreciation of the integration of various functioning parts into a balanced and organised whole.

According to Steadman, the idea of a supposed affinity between the beauty of organic, natural forms and artistic man-made forms, based on their sharing certain fundamental mathematical principles of design, was perpetuated through the seventeenth and eighteenth centuries, though with diminishing support. With the surge in archaeological study of ancient monuments in the middle of the nineteenth century, this interest in systems of classical proportion as a key to harmonic design was rekindled – both the golden ratio and the Fibonacci series were revered as the keys to the natural harmony. Much of this work from the biological perspective was brought together in D’Arcy Thompson’s On Growth and Form (1917), where he described the processes of growth and the mathematical principles behind natural forms.

The organic analogy is fascinating in its pervasiveness. Even in the biological analogies, though natural phenomena are looked at through the lens of science, there is an underlying assumption of the ‘goodness’ of natural role models. In architecture, the notion of the beauty of the organic can influence designers even when they don’t wittingly pursue it.
Fig. 2
Elevation of Santa Maria Novella by Alberti, completed in 1470, showing proportional relationships.
4. The biological analogy

Here, the term biological is used to mean something pertaining to biology as a science. Therefore the development of biological analogies coincides with the development of biology as a science. This analogy can be further divided into sub-categories: the anatomical analogy, the classificatory analogy, the ecological analogy, the growth analogy, and the evolutionary analogy. In all of these analogies there is a different approach as to what aspect of biology is being emulated. In a larger context, the biological is a part of the scientific approach, including other natural sciences.

The origin of any true biological analogy in architecture can be traced to the beginning of the 19th century, when French naturalist and zoologist Georges Cuvier (1769–1832), according to Steadman, broke from the speculative vitalist philosophies of the eighteenth century and approached the study of life with the objectivity and the empirical technique of ‘the truly scientific attitude’. Of course, that does not mean that there were no attempts to study nature before it, rather that this was the formation of what we perceive as truly scientific in the modern context. This is why in this work much of the natural analogy before the eighteenth century has been placed in the realm of organic analogy. One exception to this is the anatomical analogy, which lends somewhere between the compositional and functional interpretations of the organic analogy, but is also subject to the developments of biology as a science.

The reason why the biological analogy should be separated from the larger concepts of the organic analogy is its focus on the measurable and its removal from the esoteric and philosophical connotations regarding the relationship of man and nature. However, this area is somewhat confusing. The use of the ecological analogy sometimes includes an organic ideology. Although biology, and especially ideas about ecology have been the role model for e.g. Wright’s and Sullivan’s ideas about organic architecture, behind them are also political and transcendentalist ideals, which will be further examined in chapter 5.12, Organic architecture.

Anatomy, the description of organic bodies or their parts, gives way to an analogy that is distinctly different from the ecological one described below. In both analogies, there is emphasis on the parts of the whole having a certain undetachable function. Whereas in the ecological sense the analogy lies in the way a building should be part of and shaped by an ecological environment, the anatomical analogy draws parallels between the functions of organic parts and the functions of building parts. And as the classificatory analogy focuses mainly on visible and formal characteristics, such as the shape of a pillar, the anatomical deals with the function of that pillar and its role in the larger structure.

Portoghesi argues successfully that a certain anatomical analogy, especially that of the identification between the column and the human body, was a definitive element of Greek architecture, with a symbolic and even sacral meaning. This analogy was quite unambiguously communicated through the use of caryatids (figure 3) and telamones, and will be further examined in chapter 5.2, Classical architecture and neo-classicism.

From the eighteenth century onwards, Cuvier’s two anatomical rules have been instrumental in the anatomical analogy: first, the correlation of parts; and second, the subordination of characters. This means that for an organism to be able to survive, there must be interdependence between the various systems of the body,
Fig. 3
Caryatids of the Erechtheion at the Acropolis in Athens, Greece.
and that some of these systems are more important than others. In its simplest interpretation, the anatomical analogy as applied to architecture is present in the metaphoric comparison of the skeleton of the animal with the supporting structural framework of columns and beams or piers and vault. This comparison of animal skeletons and structural arrangements in architecture can be found at least as early as 1770, when J.-R. Perronet wrote that Gothic cathedrals were built to imitate the structure of animals. Philip Steadman points out that the metaphor of a building’s structure as an animal’s skeleton becomes especially apt in the steel-frame architecture of 1880s and 1890s Chicago, where the separation of the building’s ‘skin’ from its structural ‘bones’ is made complete.

The analogy between anatomy and architecture or structure has been made in reverse as well. Scottish biologist and mathematician D’Arcy Thompson inspired architects and engineers on his take on the anatomical analogy in his 1917 book *On Growth and Form*. In his work he, instead of drawing analogies from nature and applying them to building construction, reasons the other way around and compares mechanical structures with plant stems and animal skeletons and points out e.g. how a vulture’s wing bone is stiffened after the manner of a Warren’s truss. *On Growth and Form* would later prove to be important in the development of analogies that would lead on to bionics and biomimetics.

The anatomical analogy brings with it one very important concept that should not be forgotten: the principle of similitude. It is not possible to copy anatomical features or structures from nature and simply scale them to the needs of building design. The consequences of this principle in architecture will be discussed in chapter 5.6, *Allometry*.

The anatomical analogy has some relevance in contemporary architecture as well. Hagan argues that Santiago Calatrava’s work is an almost literal representation of structures found in nature. The structural frameworks of many of his buildings not only function like animal skeletons, but visually resemble them as well. However, Calatrava himself has insisted that the skeletal appearance of his buildings is an aesthetic preference, not a functional analogy. This would place his designs in the realm of symbolic or compositional interpretation of the organic analogy with connections to the anatomical analogy.

How does the anatomical analogy help us understand biomimicry? The description of a building’s envelope as a building’s skin is widely used in contemporary architecture, and presents fascinating opportunities for inspiration drawn from nature. An animal’s skin is integral in maintaining homeostasis, and so is the building’s skin. If we look at how organisms use their skin to regulate e.g. thermal conditions in hot climates, we can learn how to do the same with a building’s skin in a sustainable way. An especially relevant lesson from the anatomical analogy to biomimicry is the principle of similitude. Many of the structures and functions in natural organisms cannot be scaled up to a building scale successfully, and so one should be careful in the use of the analogy. Successful biomimicry relies on a sufficient level of abstraction, and this is perhaps more relevant in the anatomical analogy than any other. The process of abstracting design principles from nature will be discussed in chapter 8, *WHAT is successful biomimicry*, as well as chapter 10, *HOW to design with biomimicry*. 

*Notes*

1. *Biomimicry in Architecture*.
Fig. 4
A presentation of Goethe’s Urpflanze. Woodcarving from 1837 by Pierre Jean François Turpin.
The classificatory analogy is in relation to the biological analogy what the pursuit of classification of species is to the science of biology. A great portion of 18th century natural history was devoted to the question of classification, or systematics. This interest and effort culminated in the work of Georges-Louis Leclerc (Comte de Buffon) and Carl Linnaeus. In the scope of this thesis it is needless to venture into different methods or systems of classification – suffice it to say that the methods focused on visible and formal properties of plants and animals, not functional properties. Moreover, it was thought that through classification, all different species could be organised in such an order that possible undiscovered or lost species would present themselves as gaps in the schematic and their appearance could be thus reconstructed.

The general and overall similarities between groups of species suggested that the actual plants and animals in nature were transformations or modifications of archetypes. This theory of archetypes was elaborated and driven by botanist and poet Goethe, a member of the German school of transcendental zoology called Naturphilosophie. Goethe theorised the existence and was intent on discovering the Urpflanze, a primordial idealised archetype of the plant, of which all natural plants would be manifestations (figure 4).

It is this search for archetypes that is the driving force behind the classificatory analogy in architecture. Classification has been used as a means of finding building archetypes and theoretical principles in the hopes that it would give example to new designs – either new embodiments of existing archetypes or as lessons for a new style of architecture. The emergence of archaeology as an organised enterprise in the 18th century, as well as increased travel, provided architects and architectural writers with a pool of examples on different types of buildings. These buildings would have to be organised according to some kind of classificatory scheme much like plants in a botanist's plate, either according to their function or form, in order to be useful source material for architects facing the challenge set forth by the industrial revolution – a need for new types of buildings with unprecedented functions.

The classificatory analogy helps us understand biomimicry through a contrast of approaches. The classificatory analogy has historically focused on the formal properties of organisms, i.e. is what they are and look like, whereas biomimicry focuses on how they function. This is not to say that classification has no place in biomimicry. In order for biomimicry to be a viable design approach, we need easy access to a database of organisms and their functionalities. Some headway has been made by asknature.org, a database maintained by the Biomimicry Institute. The database is a collection of biological intelligence and biomimicry solutions organised by potential design and engineering functions, e.g. how do organisms survive in extreme heat? Or how does nature harvest water?

Some examples of the use of classificatory analogy in architecture will be given in chapter 5.5, Classificatory analogy and archetypes.
4.3 The ecological analogy

The ecological analogy concerns the environments of buildings, artefacts and organisms, and the impact of the environment on their morphogenesis. In an organism, each part or organ has a function, and its form is dictated by this function. According to Steadman, this relates to the familiar ecological analogy of 19th century functionalism and modern movement: in both animals and artefacts, form is related to function, and function is related to environment. Leopold Eidlitz (1823–1908) declared how: “In nature forms are the outcome of the environment. Environment determines function, and forms are the result of function”, and the same sentiment was declared more succinctly by Louis Sullivan in his slogan “Form follows function”.

The basic ideology behind the analogy is that in nature, organisms are adapted perfectly to their environment – be it through their innate ‘fitness’ or active adaptation – and so should buildings be. The difference of adaptation through ‘elective’ and ‘instructive’ processes will be discussed further in later chapter 4.5, The evolutionary analogy and in chapter 5.7, Theories of technological and craft evolution.

In the rise of environmental conservationism, ecological architecture has come to mean a philosophy of design where the aim is to protect and conserve the environment and natural resources, in other words sustainable architecture. These themes will be discussed later in chapter 5.17, Sustainable architecture.

The ecological analogy leads easily to comparisons between animal nests and shelters and human buildings. Pohl and Nachtigall have argued recently that the technological dwellings of humans and other living organisms and their structures create concrete possibilities for comparison. Aspects of thermal regulation, as they are embodied in e.g. polar bear fur, termite mounds or solar-driven climate systems, belong to this observational category. This brings us to a question touched upon earlier in chapter 2, Natural analogy in architecture: is architecture and the dwellings humans create ultimately a part of nature or external to it? Portoghesi has argued that human structures and animal structures, be it shells or beaver dams, are comparable. It is argued here that this is not the case. A contrasting view was brought forth already by German architect Gottfried Semper (1803–1879). He pointed out that even though old man-made monuments are in a sense ‘fossil shells of extinct organisms of society’, they are the free creations of man – unlike snail shells or coral reefs that are shaped by ‘some blind process of nature’. His main argument, and a solid one, was that humans have used their intelligence, observation of nature, knowledge, and power in the creation of their monuments. The same cannot be said of corals or snails. Beaver dams and bird nests might prove to be a different case. In this work, however, human structures are seen as distinctly separate from natural constructions like shells and nests. This does not mean that we cannot learn valuable things from the homes of animals, but ‘animal architecture’, as researched e.g. by architect Juhani Pallasmaa in his book Eläinten arkkitehtuuri – Animal architecture (2002), will not be given special focus amongst any other natural processes or phenomena in this work.

The ecological analogy is the most relevant to biomimicry in architecture, as the most difficult challenges an architect faces deal with architecture’s relationship to the environment. The challenges can be direct and physical or indirect and systemic. An example of a direct or physical challenge would be adjusting the design to a certain climate or a challenging site. An example of an indirect or systemic challenge would be the need to minimise the negative environmental impact of the building process, including the production and transportation of the building materials in
the system. This is one of the key differences between biomimetics and biomimicry: biomimetics focuses on the direct and physical challenges, whereas biomimicry takes into account the indirect and systemic challenges as well as the direct ones. More of the difference between biomimicry and biomimetics will be discussed in chapter 6, Biomimicry vs. biomimetics.

In the end, the architect plays a key role in defining that which is referred to as the environment. It can be taken to mean the physical, climatic, geographical, social or even political surroundings, the needs of the inhabitants, or the material and technological environment of the building, which affect the available manufacturing materials and tools to be used.

The growth analogy equates the process of design with growth. More specifically, it results in a process in which the designer imitates the growth or development of an individual organism, not the evolution of a species collectively. There has been some confusion between development and evolution in growth analogies, but as Steadman points out, these ideas have been vocalised prior to the advances of modern genetics. The confusion between growth and development was largely brought about by the notion that the animal embryo, as it grows, goes through stages that seem to correspond roughly to different evolutionary stages of the species. The analogy drawn from this would suggest that the designer could ‘grow’ ideas on the drawing board in a way that parallels evolution by trial and error, but in a significantly shorter time.

The important difference between the growth analogy and the evolutionary analogy is the level on which the development of the design process operates: either on the level of a single artefact or building, or on the level of an abstract design. In an evolutionary process, development happens through a series of physical iterations of an abstract design, each iteration being more ‘fit’ than the previous one. This leads to the refinement of the design, which exists as an idea in itself. In the growth analogy, however, the development happens in the design of a single artefact or building through the mental efforts of the designer. The development happens on the drawing board and in the designer's head, not through a process of successive physical iterations. When the growth analogy is taken to its logical conclusion, it means that complete design can only be achieved on the level of a single artefact, not on the level of an abstract design.

Biologist and sociologist Herbert Spencer’s (1820–1903) writings on ‘social Darwinism’ have been especially influential in the interplay of developmental and growth analogies. Spencer’s writings and the concept of the ‘survival of the fittest’ seem to have had an influence on American architect Leopold Eidlitz in the early 1880s. Eidlitz described medieval architecture and progress in construction technique through the idea that the architect could in the process of design ‘evolve’ single cells to correspond to groups of inhabitants. His loose reference can be taken to mean both to the evolution of architectural forms through time, or the development of a single design in the mind of the architect. Spencer also had an impact on Louis Sullivan, which Sullivan himself recognised in his book The Autobiography of an Idea (originally published 1924). Neither Eidlitz nor Sullivan makes a clear distinction between the metaphorical growth and evolution of a design in the architect’s mind from the ‘seed’ of an idea. Neither Eidlitz nor Sullivan makes a clear distinction between the metaphorical growth and evolution of a design in the architect’s mind from the ‘seed’ of an idea.
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Many of the analogies drawn from growth have been somewhat misguided either in the way growth has been confused with development, or in failing to understand the chemical nature of a living organism’s growth. Growth interpreted as a series of incremental additions, however, has potential if we interpret growth in nature in a broader sense. Not just living organisms grow, but also crystal structures and other inorganic entities, and precisely by incremental additions. It is in this realm that the growth analogy holds promise for biomimetic solutions in architecture.

A clear way of implementing the growth analogy in architecture is by way of addition. In this case growth is analogous to the way a physical space or construction increases in volume or in the number of units it houses. Most often this kind of growth exists on an urban scale. The movements of Metabolism and Structuralism illustrate some examples of growth by addition. Growth in spatial structures can also be enabled in a short timescale with deployable structures, and might increase in importance with the advent of space architecture – lightness of structures and transportation costs are key parameters in space missions. Deployable structures are not, however, necessarily analogous to growth. The mechanisms and technologies used in deployable structures can be inspired by adaptive mechanisms in organisms, for example the non-autonomous movements in plants. Some of these adaptive mechanisms will be introduced in chapter 10, HOW to apply biomimicry.

4.5 The evolutionary analogy

The theories of evolution can be used to draw analogy in many ways – either in analysing how artefacts might have developed through time, or in imagining ways in which evolutionary principles could be used in the design process in an accelerated way. The wording of theories as plural in this instance refers to the applying of either Darwinian or Lamarckian evolution theories to design. The following is meant to be a very brief review of the influence of evolutionary theory on the interpretation of the history of architecture and the design of artefacts and buildings. It is not possible or desirable here to go through all developments of evolutionary theory of the last two centuries, so the focus shall be on the two most important approaches: the Darwinian and the Lamarckian theories. The evolutionary analogy can be used in two different ways: first, to analyse and describe existing phenomena in the history of architecture; and second, and as a design approach in which the designer tries to emulate the evolutionary process. In design evolution, rather than subjecting the design to actual conditions to test its accuracy or suitability, the designer uses his intellectual faculties to theoretically test the design through the power of imagination, as suggested by Christopher Alexander.

The Lamarckian theory of evolution precedes Darwin’s ideas, but was for some considerable time defended as a valid theory by Darwin’s contemporaries. In contrast to Darwin’s theory of elective evolution, French naturalist Jean-Baptiste Lamarck advocated the idea that organisms evolve through the instruction of their environment and the inheritance of acquired characters. Lamarckism, i.e. the theory of instructive evolution, lays emphasis on the ability and effort of an organism to be able to adapt to its surroundings. During the life of an organism various forces affect and shape the organism towards an optimum – parts that are in frequent use become more highly developed and parts that are less necessary slowly disappear.
In a Lamarckian analogy, artefacts are able to evolve through use and mending, not just their abstract designs. How the theory of instructive evolution has been used to explain technological and craft evolution will be discussed in a later chapter.

The Darwinian evolutionary analogy equates heredity with copying. The idea is that as plants and animal species evolve through time by experiencing small random mutations and permutations in their congenital attributes which, if they contribute to the "fitness" of the organism, will be inherited by the next generation and through accumulative effect change the organism. So does the design of the object evolve through small accidental permutations made by the craftsman in successive copies, and through "generations" of copying these permutations accumulate into a changed object. This theory has been applied to the study in which tools and buildings are produced and developed in ‘primitive’ cultures. This view of design emphasises the role of tradition and almost erases the craftsman or designer – they are only makers of copies, and produce variety by lack of skill in copying, the unpredictable nature of materials and so on, but not through their innovative urge or creative powers. Steadman makes note that in this analogy it is not the individual artefacts that evolve, it is abstract designs.

One significant distinction should be made when drawing analogy from organic evolution to technological evolution or the evolution of artefacts: the different way in which new ‘species’ are formed. In organic evolution, once diverged, two species cannot join together to make a new one – new species are only formed when an existing one diverges into two new ones. In technological evolution, however, new designs for objects can be formed by merging together existing ones. Cultural and technological evolutions are strictly neither Lamarckian nor Darwinian, but they work in a way that can be described by both evolutionary analogies. A design or object can inherit features through successive copying of accidental modifications, as well as be refined during the course of its use and then be used as a model for an improved design.

This thesis will not dive further into the theory of autoevolution as a relatively new and not widely endorsed theory. As a short introduction it can be mentioned that the theory of autoevolution, introduced by molecular biologist A. Lima-de-Faria in the late 80’s, describes life as a physical and chemical phenomenon caused by a tendency towards self-assembly. It links together the organic and inorganic worlds by suggesting that between animal, plant or inorganic natural material such as rock crystals there may be an atomic homology with common ancestors in the field of structural configurations. In short, the theory of autoevolution does not exclude adaptive processes, but it doesn’t consider them the driving force behind forms. For the purposes of this thesis it is sufficient to say, that even if the Darwinian theory of natural selection or the ‘survival of the fittest’ has been challenged by other modern evolutionary theories, certainly the solutions and phenomena in nature are suitable to their environments in an exemplary way. Through evolution, be it described as Neo-Darwinian or autoevolutionary, the natural world is a research & development laboratory unparalleled in its scope and longevity. Our built environment is subject to the same physical and chemical laws, and as such can benefit from the developments in nature.

Evolution in itself is instrumental in biomimicry, but not in an analogous way. The idea behind biomimicry is essentially that the process of ‘evolutionary’ design by the architect can be omitted by simply stealing solutions from nature that have already
been fine-tuned by actual evolution. However, it is helpful to understand the ways in which evolutionary analogies have been drawn, as they influence the way in which we value the ‘fitness’ of designs. Like nature is two things: a physical and quantifiable world and also our cultural construct; so evolution is both a mechanism in nature, but perhaps even more importantly also the evolutionary theories humans have developed. That which influences our design processes is more the theories than the actual mechanism.

Despite biomimicry not relying on the evolutionary analogy, design processes inspired by evolution can be a valuable addition to the biomimicry process, especially in the task of material optimisation of structures (see chapter 5.15, *Evolutionary design by computer*).
5. Examples of natural analogy in architecture and design

5.1 Biomorphic and zoomorphic architecture

Biomorphic architecture uses allusions to natural forms, mostly for aesthetic reasons and for symbolic association, without special focus on the performative capacities of the biological source of inspiration, or the evolutionary and physical reasons for its morphology. The idea of biomorphism is intertwined throughout architectural history and does not refer to any specific period of design. The line between biomorphic and zoomorphic architecture is an elusive one, and perhaps unnecessary to draw. The biomorphic or zoomorphic analogy can be a three-dimensional imitation of animals or their parts, or a two-dimensional mapping transferred to a building. Biomorphism and zoomorphism are visual or symbolic analogies, and are difficult to place to a historical timeline. Both ‘morphisms’ are good examples of a label being attached to buildings in retrospect – the architect did not necessarily think of their design in connection with the term when designing.

Zoomorphic architecture uses animal morphology as a direct model for architecture. This mimicking of animals or their parts is different from the anatomical analogy – zoomorphism takes the shape of the animal or its parts as a model (figure 5), whereas the anatomical analogy is concerned with the function of different body parts, or their dimensional proportions. Historical examples of zoomorphic architecture include the 16th century Parco dei Mostri in Bomarzo (figure 6), and the designs of French Jean-Jacques Lequeu (1757–1826), as well as James Lafferty’s 1883 design for a seaside attraction, Lucy the Elephant (figure 7).

5.2 Classical architecture and neo-classicism

It was mentioned earlier in chapter 4.1, that a certain anatomical analogy, especially with the human body, was a definitive element of Greek architecture. The role of the organic analogy in Greek classical architecture and its later mimicking in neoclassicism is touched upon only briefly here. The organic analogy was in a great role in classical Greek architecture in general. The layout of the Acropolis (figure 8), for example, appears on plan to be a haphazard composition – but when the visitor approaches, unfolds as a harmonic and logical sequence in a balanced natural universe. As mentioned earlier, both Plato and Aristotle required that any literary work should have and ‘organic’ form, and be more that the aggregation of its parts. This philosophical ideology can be argued to apply to architecture as well as a part of the cultural ideology of the inherent goodness of natural, organic composition. Hagan writes that the classical orders are also ‘organic’ in their relating of architecture to ‘nature-as-human-body’, Doric columns being analogous in their strength and simplicity to the male body, and Ionic columns analogous in their delicacy and attenuation to the female body. This analogy with the human body is made very literally in the use of caryatids and telamones, human figures carrying the weight of a building in lieu of pillars and pilasters. The compositional aspect of organic
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Above left: The form of Eero Saarinen’s TWA terminal at John F. Kennedy Airport, New York (1962) evokes thoughts of flight with its allusion to birds’ or beetles’ wings.

Above right: An entrance in Parco dei Mostri.

On the right: Patent drawing for Lucy the Elephant.
harmony, and especially the human form as a model for proportional harmony was later emphasised by Vitruvius.47

During the eighteenth century, the publishing of measured drawings of ancient sites expanded the available information relating to architectural history,48 and in no small measure, the interest towards both Greek and Roman classical architecture. With it came an appreciation of the organic tradition of Aristotle and Plato and later renaissance architecture.

In 1753, when the Abbé Laugier wrote his treatise on architecture called *Essai sur l’architecture*, it can be argued that he was still validating culture through nature. At least, validating culture through the cultural construction of nature that he imagined valid: a guide to the classical Orders. Laugier demonstrated, notoriously without any archaeological evidence, that the origins of classical architecture lie in the *primitive hut* composed by nature itself – columnar trees still rooted to the ground, a pediment made with their branches, and an entablature made with still more branches (figure 9). According to Hagan, the neo-classical architecture of eighteenth-century France abstracted organisational principles from a primitive and rough model of the hut as much as Alberti abstracted proportional relationships from nature.50 Laugier’s *primal hut* is not to be confused with Semper’s *Urhütte* from a century later, from which all architecture according to his theory began.50

5.3 Renaissance architecture

Renaissance architecture followed the tradition of organic analogy set out by Plato and Aristotle: that nature itself was an imitation of the divine order, and should thus be imitated to achieve beauty. According to Hagan, this practice of ’architecture imitating a nature that was itself an imitation of the divine order’ reached its pinnacle in the designs and writings of Leon Battista Alberti. His 1452 treatise *De Re Aedificatoria* established that beauty was found in a kind of numerology: architecture should not imitate the material world as such, but the underlying perceived mathematical structure that was the blueprint for the harmonic ratios found in nature. Of particular importance were the ratios of the human body, and the relation of the parts to the whole.51 As such, a connection can be made to later proportional systems, as mentioned in chapter 3, *The organic analogy*.

During the renaissance, the view towards nature was that of man being a part of it, not separate from it or superior to it. Nature and art were governed by *coincinnitas*, and all-encompassing harmony between the parts and the whole.52 The affinity to the proportions of the human body can be argued to tangentially touch on the anatomical analogy as well, as some of the analogies made during the Renaissance were relatively simplistic – for example matching the two-dimensional layout of the building to that of the human body part for part (figure 10), or following the bilateral symmetry of the body in the mirror symmetry of a building’s parts.53 However, this parallel between the human body and the architectural composition goes no further to draw parallels between the structural functions of parts, as is more common in the scope of the anatomical analogy.
Fig. 8
On the right: The site plan of the Acropolis showing the organic layout of the area.

Fig. 9

Fig. 10
Below left: Francesco di Giorgio (1439–1501), the proportions of a human body superimposed on a church plan.
Much of the natural analogy seen to exist in Gothic architecture has been seen afterwards, and superimposed on it by writers and architects analysing the Gothic style during its revival. For this reason, the two historically distinct periods will be discussed here in the same chapter.

As already mentioned in chapter 4.1, The anatomical analogy, a comparison between the structural arrangement in buildings and the skeletons of animals was made at least as early as 1770, when J.-R. Perronet wrote of Gothic cathedrals that:

"The magic of these latter buildings consists largely in the fact that they were built, in some degree, to imitate the structure of animals; the high, delicate columns, the tracery with transverse ribs, diagonal ribs and tiercerons, could be compared to the bones, and the small stones and voussoirs, only four or five inches thick, to the skin of these animals."

It can be argued, however, that Perronet’s anatomical analogy was falsely applied, and the builders of Gothic cathedrals imitated nature only in the sense that it embodies God's divine order on Earth – an organic analogy under Hagan’s 'top-down' model (see chapter 3). Architect Pierre Patte (1723–1814) also dismissed Perronet’s anatomical analogy by pointing out that such a hard and rigid material as stone could not be properly compared to the elastic and living structure of the body.

In the late eighteenth century, Sir James Hall went to great lengths to demonstrate the 'naturality' of Gothic architecture compared to classical architecture (figure 11). The way in which he arrived at his conclusion was by building a Gothic church out of ash wood poles and willow rods, tying the rods to the poles and bending the poles – thus achieving the three main characteristics of Gothic architecture, the clustered column, the pointed arch and the branching roof.

According to Steadman, a recurrent claim in nineteenth-century architectural theory is that certain historical buildings, above all the French Gothic cathedrals, exhibit beauty because of an absolute rationality and economy of structure. This so-called ‘Gothic Rationalism’ had its greatest spokesperson in Eugène Viollet-le-Duc (1814–1879), who again following the anatomical analogy saw the pattern of ribs in Gothic vaulting. Viollet-le-Duc emphasised the intellectual basis and underlying rational structural principles of Gothic building, and claimed that like the form of a plant could be deduced from of its leaf, so could the form of a monument be deduced from a cross-section of an architectural member. Viollet-le-Duc’s views on Gothic cathedrals touch on the ecological analogy as well. To illustrate the typical features of a cathedral, he drew out the ‘ideal cathedral’ (figure 12), not perfect, but typical, which provides a rational exposition of the structural and functional logic of every member and their assembly into a coherent whole. This is reminiscent of the classificatory analogy and Goethe's search for the Urpflanze, an archetype that includes the components of all possible iterations. An evolutionary analogy is also brought into light when he describes medieval architecture as a whole being an organism ‘which develops and progresses as nature does in the creation of beings’.

More of the evolutionary analogy will be discussed in chapter 5.7, Theories of technological and craft evolution.
Fig. 11
Above right: The natural wooden origins of Gothic piers and arches as shown by Sir James Hall in Origins of Gothic Architecture (1797).

Fig. 12
Below right: Viollet-le-Duc’s Cathédrale idéale.
An example of classificatory work in search of new architecture is architect and writer J.N.L. Durand’s synthetic method of architectural composition set forth in 1819 in his *Leçons d’Architecture*. He drew on his previous work of classificatory analysis of building types, their history and function to produce a method where the architect arranges pre-designed elements symmetrically around the principal and subsidiary axes of the building. Steadman points out that Durand’s compositional procedure is essentially a formal and geometrical one, and not based on function (figure 13). As new, more functional criteria for the classification of species arose in the first half of the 19th century, the analogies drawn in architecture also shifted to a more functional view, with a focus on the organic relation between the parts.60

More recently, the design lab Certain Measures has done research into typologies and categorising buildings. Their software *Spatial Recognition* uses techniques from facial recognition to find buildings by form. From the drawing of a plan outline, the tool can find all of the buildings in a given city with that shape.61 How this helps to understand scenarios and precedents in design is a matter for further discussion that will not be delved into further in this thesis.

Allometry, a term used in biology for the study of the relationship of body or element size to its shape, with its basis in the principle of similitude – that is, that in bodies which are similarly shaped, the relations of the parts will vary with the size. A scale model cannot give a true-to-scale representation of a structure’s mechanical performance. Bridges, girders or other structures, which are of exactly similar design, will vary in strength for given thickness according to their absolute size, which results in a problem of scaling.62 The relevance of this kind of effect on systems of architectural proportion and to engineering and structural challenges in building have been pointed out by several writers – the principle was already appreciated by Galileo, and later picked up by Cuvier, Spencer and D’Arcy Thompson, among others.63

The study of the problem of size and its consequences on form has been developed in biology by British biologist Julian Huxley (1887–1975) and others. There is a connection here to be made with the growth analogy, as Huxley was interested in giving a mathematical expression to the growth of organisms. Because of the principle of similitude, when animals or plants grown, that is increase in their absolute size, their proportions also change.64 So when ‘growing’ buildings, the proportions of them should change as well. Although buildings can’t grown in an organic sense, their size can be changed in incremental additions – this idea of growth is very different from the one discussed earlier in the growth analogy, where the idea was that of growing a building from the seed of an idea to the matured design. In terms of the built environment, the incremental growth is most likely to resemble an organic process in unplanned, high-density urban areas.

Regarding architecture, specifically columnar structures, Viollet-le-Duc points out how proportions should not be determined in any absolute way, but in relation to the material, the design in question and its purpose.65 The principle of similitude brings about other concerns as well, regarding scaling of architectural designs, as Steadman describes in *The Evolution of Designs*. A building’s total space is most likely expressed in terms of total floor area, albeit misleadingly, as a certain floor-to-ceiling height is assumed, and the effective amount of space is actually a function of the built volume. Other important quantities, however, are related to area – the site
area, the area of the building envelope, or the floor area reachable by daylight. In effect, a form of a large building cannot be the enlargement of a smaller building.\textsuperscript{66} Buckminster Fuller applied the principle of similitude to his geodesic domes, showing how larger domes will lose heat slower than smaller ones.\textsuperscript{67}

Architect Ranko Bon was the first to investigate specifically ‘allometric’ relationships in architecture.\textsuperscript{68} He has done studies in the ratio of surface area to volume in a sample of historical buildings, and found an applicable allometric relationship. He has also looked at the floor areas of the buildings compared with the total length of ‘movement patterns’ with similar results.\textsuperscript{69} Philip Steadman has replicated Bon’s findings theoretically, and points out that the development of 3D modelling of cities has made it possible to study allometry and scaling empirically in buildings on a larger scale.\textsuperscript{70}

\textit{Fig. 13}

\textit{Building ensembles in J-N-L Durand’s Précis of the Lectures on Architecture (1802).}
The chapter will discuss briefly how technological evolution, or the evolution of artefacts and designs has been seen through Darwin's theory of elective evolution, as well as Lamarck's instructive evolution – and how, at least for a certain time, it affected the way vernacular architecture and the role of the designer was viewed. In a 'Lamarckian' theory of technological evolution, artefacts are able to evolve through use and mending, not just their abstract designs. The 'Darwinian' theory of technological evolution, however, equates heredity with copying. The design of an object evolves through small accidental permutations made by the craftsman in successive copies, and through 'generations' of copying, these permutations accumulate into a changed object. It has been especially anthropologists and archaeologists who have pioneered a scientific and explicitly Darwinian study of the way in which tools and buildings – in primitive cultures at least – are produced and developed (figure 14). In a Darwinian view of craft evolution, it is the abstract designs that evolve, not individual artefacts. The theory of the evolution of decoration, and many of the arguments for the Darwinian analogy, rest on the assumption of the extreme conservatism of the craftsman and his unwillingness or incapability to make significant alterations to existing and traditional designs.

One significant distinction should be made when drawing analogy from organic evolution to technological evolution or the evolution of artefacts: the different way in which new 'species' are formed. In organic evolution, once a species has diverged into two, they cannot join back together to make a new one. In organic evolution, new species are only formed when an existing one diverges into two new ones, whereas in technological evolution, new designs for objects can be formed by merging together existing ones. It could be argued that this is the most usual way of designing new objects: taking the desired functional aspects of existing designs and merging them into a new whole. Cultural and technological evolutions are strictly neither Lamarckian nor Darwinian, but they work in a way that can be described by both evolutionary analogies. A design or object can inherit features through successive copying of accidental modifications, as well as be refined during the course of its use and then be used as a model for an improved design.

In the Evolution of Designs, Philip Steadman states that the theory of evolution of decoration has had a significant relevance to the study of history of architecture. The theory prevalent in the nineteenth century was that changes in decoration, like the changes in the overall forms artefacts, were produced by gradual and subtle changes – motifs were transmitted through a process similar to that of successive copying with slight modification in each 'generation' of copies. This idea of evolution of decoration might explain the presence of skeuomorphs – decorative forms deriving from structure, often gradually abstracted almost beyond recognition. Steadman goes so far as to argue that excluding the decorative possibilities of material textures and applied sculpture and mural painting, almost all other architectural decoration has its origins in structure "either in the survival of functionally superseded forms, or in the application of previously structural forms to contexts where they are the structurally functionless".

With regards to technological and craft evolution there is quite often an assumption of the constant betterment of things due to the evolutionary process. New designs and artefacts are seen as superior to their precedents, at least in functional and utilitarian terms. This, however, is not the way biological evolution works, and where the theories of technological and craft evolution differ from their perceived analogue. Biological evolution is a non-deterministic process. Steadman
argues that in this sense architectural design and the process of biological evolution are similar: evaluation criteria and development targets are in constant change and subject to adaptation in changing environments. This makes architecture (and biology) different from most engineering sciences. Technological innovation, e.g., concentrates on the optimisation of clearly defined functions with fixed boundary conditions. In architecture, however, a quantifiable ‘optimum’ is not something that can be reliably achieved except in some technical or economical parameters, for example the optimisation of energy consumption or of material use. The ‘optimum’ of aesthetic, spatial, urban, or social qualities of a design cannot be quantifiably measured.77

Steadman argues that the idea of relentless and deterministic upward dynamic in technological progress is particularly strong in Buckminster Fuller’s writings. For Fuller, the principle he dubbed as the 'Dymaxion' principle denotes a trend always towards higher speed for vehicles, greater efficiencies for machines, better performance at a lower monetary, material and energy input.78 The 'Dymaxion' principle is an evolutionary analogy only if one sees evolution as a linear process towards an ideal of 'somehow always 'better' – this, however is not necessarily the case, as the Darwinian evolutionary process leads to a 'fit' solution and, once this relative 'fitness' for the operative environment has been achieved, there is no incentive for further change towards a higher level. As Steadman points out, Darwin did not propose – as Spencer did – any law of evolution as such, or any goal or state towards which it was directed. He only described a mechanism for the operation of selection that depends on certain assumed laws of heredity and variation.79 In other words, the most 'fit' species in a given environment does not need to be the most developed – it can be just as well a 'higher' or a 'lower' species.80
The terms *biotechnique* and *biotechnics* have been used by multiple writers and architects to describe slightly different things, and the origin of the concept is hard to pinpoint. The essence is this: in the evolution of plants and animals, nature has already made a great variety of ‘inventions’, and the designer could through diligent study of the engineering of nature find a solution to all arising technical needs.81 The idea underlying principle in biotechnics and biotechnique82, that instead of technological evolution needing to be time-consuming, it could ‘borrow’ the time already invested in the organic evolution of natural counterparts to human artefacts, is shared by *biomimetics* and *biomimicry*. We will arrive at a more detailed definition of these concepts in chapter 6, *Biomimicry vs. biomimetics*.

Philip Steadman traces the history of the concept of *biotechnics* to the 1870s and onwards, and to popular books on the subject of analogies between nature and machines. One of these writers was the Reverend J.G. Wood, who wrote *Nature’s Teachings: Human Invention Anticipated by Nature* in 1877, cataloguing the parallels between nature and art. Several other writers followed the general narrative of *Nature’s Teachings*.83 The Austro-Hungarian botanist Raoul H. Francé carried on the tradition in his 1920 book *Die Pflänze als Erfinder (Plants as Inventors)*, where he described how a ‘biotechnic’ design approach examines the technical arrangements of unicellular organisms and other aesthetic forms in nature in order to manufacture economical constructions. According to Francé, in order to find a technical solution to some given need, the ‘biotechnical student’ must seek the solution of the identical need in some biological example, and then imitate that arrangement.84

This concept of biotechnics and biotechnique attracted the attention of designers in the late 1920’s and 1930’s. According to architect, historian and theorist Stephen Phillips, Francé’s writings had a substantial impact on the members of *G* magazine, especially Moholy-Nagy, Ludwig Mies van der Rohe, and at least indirectly, Frederick Kiesler, who went on to expand these synthetic design ideas through his theory of *correalism*. Referring to Francé’s writings, Moholy-Nagy coined the term *biotechnique* to describe a formal methodology that specifically applied seven basic elements to all design – the crystal, sphere, cone, plate, strip, rod, and spiral.85 The argument for these seven ‘biotechnical elements’ was summarized in Francé’s writings: "The laws of the least resistance and economy of action force equal actions to lead to the same forms, and force all processes in the world to develop according to the law of the seven fundamental forms."86 According to Moholy-Nagy, what was important was to follow the general principles of nature’s methods.87 Kiesler made a further distinction between the terms *biotechnics* and *biotechnique*: the former meaning a design method which involves turning natural forces toward human needs, and the latter as "nature’s method of building, not... man’s."88 Hagan argues that it was Moholy-Nagy’s influence that helped Alvar Aalto make a style shift within modernism from a “law-abiding International Style to an architecture that imitated nature rather than the machine”.89

Architecture historian Lewis Mumford first used the term *biotechnique* in his 1934 book *Technics and Civilization*. He used the word to describe a period of architecture when machines would completely integrate with human needs and desires to support a communist lifestyle by eliminating social distinctions and providing the masses with more leisure time. According to Mumford, architects and planners would, through close observation, analysis, and abstraction of nature, be able to study the environment to assimilate bodies and machines.90 Steadman suggests that for Mumford, the idea of *biotechnique* does not pertain so much to any specific biological models in the design process so much as it describes the ideals of economy of
Fig. 15
On the right: The underside of a Victoria regia leaf.

Fig. 16
Below: The structure of the Fiat Factory in Turin by Giacomo Matte-Trucco.
material and effort and the process of growth in the philosophy of larger Utopian political and economic goals. Mumford’s view of biotechnic, however, comes from biologist and pioneer town planner Patrick Geddes, who coined the term in his 1915 book *Cities in Evolution*. In the architectural context Mumford uses the term to describe a design philosophy which favours light, low structures instead of the massive and monumental, and which suggests that a building’s mechanical services could be simplified and decentralised.

An example of biotechnics can be found in the concrete floor structure of the Fiat Factory in Turin (1916–1926), as pointed out by Karel Honzik in 1937 in his *Note on Biotechnics in Circle*, and yet again by Steadman, compared with the underside and visible stiffening structure of the *Victoria Regia* water lily. It is not known if the designer, originally a marine architect and engineer, Giacomo Matte-Trucco, had a specifically biotechnical vision, but the finished design easily lends itself to this kind of interpretation.

**5.9 Correalism**

*Correalism*, a term coined by architect, theoretician, and artist Frederick Kiesler in the 1930’s, refers to the study of the relationships (correlation) between man and his natural and technological environments. As was established in the previous chapter, Kiesler was equally interested in correalism and biotechnique at the same time in his career. For Kiesler, *correalism* was the science and *biotechnique* was the method to producing a total environment, a *Gesamtkunstwerk* of effects.

Stephen Phillips suggests that Kiesler derived his use of the term *correlation* from theories of animal and plant morphology described by Geddes in his 1911 book *Evolution*. Kiesler used the term to describe the practical application of structural form to bodily function in a situation where the whole is constructed in relation to its parts. Applied to architecture, this means the relationship between architecture, human bodies, and the environment.

The idea of correlation of parts in biology was already stressed by Georges Cuvier in his two anatomical rules: the ‘correlation of parts’ and the ‘subordination of characters’. For Cuvier, ‘correlation of parts’ meant the interdependence of various systems or organs in the body, and the ‘subordination of characters’ meant that certain bodily systems or organs had greater functional significance than others. In this sense, Kiesler’s *correalism* can be seen as having a link to the anatomical analogy – he even goes so far as to describe his Endless House as a living organism.

The basic ideas of *correalism and biotechnique*, according to Steadman, are as follows:

1. Tools and architecture are created to mediate between man and the natural environment.
2. Technology serves man’s basic needs (for example his health).
3. There’s a place for a new science studying man and technology’s relationship.
According to Kiesler’s *Manifeste du Corréalisme*, the final form of the building should emerge organically, like the “multiple, specialized functions of organs are already contained in the amorphous embryo of the human body”. As an embodiment of his vision of corréalism and biontechique, Kiesler envisioned the Endless House (1947–60), a flexible habitat where the spaces would be “as elastic as the vital functions”, and the house itself a living organism, not just an arrangement of dead material. The house was never built in full scale.
5.10 Functionalist aesthetics

As described in the organic analogy, the general aesthetics of functionalism value the notion of the organic as something that is beautiful because it is fitting. A well-designed artefact that fits its purpose is seen as beautiful specifically because this fitness is recognised. This tradition follows two strands in the functionalist aesthetics and later in the aesthetic philosophies of the modern movement: the biological analogy looking towards nature, and the technological analogy looking towards mechanical works and civil engineering. Both these strands share an appreciation of the integration of various functioning parts into a balanced and organised whole. According to Steadman, functionalism in the modern movement in architecture has “made a virtue out of the positive emphasis of the means of construction, of the material, and of the purpose of each part.”

According to Hagan, when the rhetoric of the machine as a model was most strident, there were architects like Wright, Neutra, Scharoun and Aalto insisting on “nature remaining a model for architecture.” Alvar Aalto was interested in the complex example one could see in nature – he looked to the variety generated from the unit of the cell, in contrast to the monotony of mass production. Moholy-Nagy was an advocate for nature in Bauhaus, maintaining that if students pursued functionalism the correct way, they would inevitably, even without studying natural models, arrive at a solution ‘agreeing with nature’s own creations’. Along with Moholy-Nagy and Aalto, also Richard Neutra argued that humans might be on the losing side in seeing nature as an imitation of culture and not the other way around. Neutra saw the complexity in nature as a model for a more complex and ‘natural’ way of organizing space, and possibly enriching modernism.

5.11 Purism

In the 1920s Le Corbusier and Amadée Ozenfant developed the artistic theory of purism and advanced the concept of the objet-type. The core of this theory was the idea that certain stereotyped and the purists saw all mass-produced objects as the end products of technological evolution. This meant that objects could be seen as extensions of the human body or even as substitute organs. The evolutionary analogy and theories of craft evolution come to play here: tools are seen as exosomatic parts of human evolution, developed through instructive cultural evolution. According to the Purists, mechanical evolution and natural evolution are similar processes, and conform to identical natural laws, and thus the aesthetic qualities in machines and organisms have a common origin.

The Purists maintained that the operation of the law of selection in these evolutions is essentially a matter of economy – the evolution of tools and machines is towards maximal performance for minimal cost or effort. Steadman goes on to point out that neither Le Corbusier nor Ozenfant meant that the satisfaction of functional and utilitarian needs in design would by itself necessarily mean that the result must be beautiful. Le Corbusier thought that in architecture, the evolutionary process of producing objets-types for buildings had lagged behind engineering and industrial design, and modern architects should be urgently working on this. The difference between this search for architectural objets-types and for example Durand’s search for archetypes lies in the analogy drawn from nature: Corbusier and Ozenfant strove for archetypal results by mimicking evolution, whereas Durand focused on categorizing and analysing a set of supposedly predetermined building types to find ones not yet discovered (see chapter 5.5, Classificatory analogy and archetypes).
Steadman points out the affinities between the Purists theory of objet-type and of mechanical evolution and Francé’s biotechnical programme discussed in the chapter on biotechnics and biotechnique. What these approaches have in common is the stressing of satisfaction of function within the strictest economy of means (figure 18), and with the resulting evolved forms supposedly made up out of a limited pool of geometric components.  

**Fig. 18**

Biotechnics, purism and the functional aesthetics of mechanical evolution share some basic ideals: in the overlapping middle is the satisfaction of function with the strictest economy of means.
The French periodical *Revue Générale de l’Architecture* is credited with first launching an ‘Organic Architecture’ in 1863. According to the publication’s editor, the style got its name because it was to the Historic and Eclectic Schools what the organised life of animals and vegetables is to the unorganised existence of the rocks and the sub-stratum of the world.\(^ {111}\) The coining of the term has been subsequently attributed to Frank Lloyd Wright and his view of architecture as an asymmetric, natural, easy response to the demands of the site and the functions needed. There is nothing especially biological in the organic architecture of Louis Sullivan and Wright, as for their view also implied a certain political involvement: organic architecture should grow naturally out of the society which produced it.\(^ {112}\) Sullivan’s ideals concerning architecture lean more on a symbolic interpretation of the organic analogy, whereas Frank Lloyd Wright’s interpretation places emphasis on the compositional interpretation of the organic. Steadman points out that what Sullivan and subsequently Wright meant by ‘organic’ in architecture can be traced back in one direction to functionalist ideas and in another to the tradition of Romantic naturalism and the picturesque in architecture.\(^ {113}\)

Wright was influenced by the architectural ideas of Louis Sullivan, who in turn based his ideals on German transcendentalism. Sullivan’s architectural style was a reflection of his intuition of nature’s processes of creation. Sullivan had a pronounced political aspect to his work, striving for a ‘democratic architecture’, which would affect human behaviour and enable true democracy. According to his transcendentalist ideals, however, the most important aspect of architecture for Sullivan was to remind humans of their need to establish an intimate bond with nature. This effect he would evoke mainly with symbolic elements – anthropomorphism, vertical elements in a facade evoking tall trees, or colours and patterns serving as reminders of nature.\(^ {114}\) However, to simplify Sullivan’s view of the analogy to a symbolic level would do him a disservice. As mentioned earlier, Herbert Spencer’s evolutionary and functionalist ideas, as well as Darwin’s, influenced Sullivan (see chapter 4.4, *The growth analogy*).\(^ {115}\)

According to Philip Hoffman in his book *Frank Lloyd Wright: Architecture and Nature* (1986), Wright considered Gothic architecture to be closer to the organic than any other, as it would not succumb to notions of outward symmetry without meaning or value. He was impressed by the idea that a building might aspire to a level of organisation as high as that of an organic entity.\(^ {116}\) The importance of Wright’s valuing of Gothic architecture ties in with Wright’s notion of the *organic* and the tradition of organic analogy. Form, according to Wright, should follow a single grammar, and beauty would follow naturally from this harmony (figure 19).\(^ {117}\)

In contrast with organic architecture, some architectural ideologies in the twentieth century have taken a different approach to organisational principles, yet drawing from natural analogies. Both *structuralism* and *metabolism* are concerned with organisational principles drawing analogy from nature. Structuralism has an inherent belief that phenomena of life and culture are only intelligible through their interrelations and relation to a larger structure. Aldo van Eyck’s Amsterdam’s Municipal Orphanage (1957–60) is an example of structuralism with its clearly defined modules in a more or less flexible arrangement (figure 20).\(^ {118}\) Metabolism as stated by Kisho Kurokawa in the 1960s referred to the implementation of change, exchange, and constant renewal into architecture. Elements were to be organised according to natural role models like trees, skeletons, DNA, etc (figure 21).\(^ {119}\)
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Fig. 19
Above: Wright’s ideals of organic architecture are demonstrated in his 1935 Fallingwater, a residence for the Kaufmann family.

Fig. 20
On the right: Aldo van Eyck’s Amsterdam’s Municipal Orphanage (1957–60) is an example of structuralism.
The term *bionics* was coined by military doctor Major Jack E. Steele in 1958 to denote a field of study dedicated to copying real organs in the design of medical prostheses, e.g. artificial limbs and heart pacemakers (figure 22). This has paved way to cybernetics and anthropomorphic robot design. Cybernetics is a transdisciplinary approach for exploring regulatory systems – their structures, constraints, and possibilities. The term is often used in a rather loose way to imply controlling any system using technology.

Since the 1960s *bionics* has developed into a branch of modern engineering that has systematised the study of biological mechanisms that promise to have practical applicability in man-made devices. It can be argued that biological models serve as sources for conscious inspiration only in areas unsupported by theoretical base – with focused research, the biological analogy soon turns to generalised and theoretical knowledge and is no longer directly bioinspired.

There may be room for misunderstandings because of the differing use of the term bionic in different languages and cultural contexts. As Petra Gruber points out in her book *Biomimetics in Architecture* (2011), the German word *Bionik*, derived from the English *bionics*, is equivalent in meaning to the term *biomimetics* in the English-speaking world. However, the confusion is not necessarily a dangerous one – biomimetics is essentially a further and wider application of bionic principles onto fields other than engineering and robotics. The fields referred to in German as *Bau-Bionik* and *Architektur-Bionik* will be translated in this thesis as *building biomimetics* and *architectural biomimetics* respectively.

As explained previously in chapter 4.4, in the growth analogy the designer imitates not the evolution of the species collectively, but rather the process of growth of the individual. Inherent in this analogy is an idea that metaphorically, from the ‘seed’ of an idea, the designer might ‘grow’ a design that could flourish in the ‘environment’ of the designer’s critical evaluations. This theory is heir to the ideas of Eidlitz and Sullivan, who in turn were influenced by Spencer. Despite the confusion between the mechanisms behind evolution and growth in the ideas of these architects, the idea of ‘growing’ buildings has garnered continued interest from contemporary designers.

Some of the techniques that have been of interest to architects are the cellular automaton and the L-system. John Frazer’s Universal Constructor, which was built in 1990 at the Architectural Association in London, was a 3D cellular automaton. The L-system, or L-grammar, named after botanist Aristid Lindenmayer, is a rule-based system for representing the topology of the branching structures of plants – according to Steadman this can be seen as a mathematisation of Goethe’s *Urpflanze*. The L-system can also be used to generate structures and surfaces that are more closely approximate to those of buildings rather than plants.

The many possibilities for the uses of these techniques, but it seems that most focus on the resultant morphology of growth only, not the actual (chemical) process of a plants growth. Martin Hemberg has developed the Genr8 tool for designing surfaces at the Emergent Design Group at MIT and the Emergent Design and Technologies Group at The Architectural Association in collaboration with Una-May O’Reilly, Peter Testa, and Achim Menges. The tool enables the growth of digital 3D surfaces,
Fig. 21
The icon of metabolism, Kurokawa’s Nakagin Capsule Tower, 1972.

Fig. 22
A bionic hand with a skeletal structure modelled after the human hand.
Evolutionary design by computer is process in which the designer can create a kind of simulated and speeded up version of technical evolution. This is done by using mathematical or computer models to represent form, context, and their interaction. Software and algorithmic techniques developed since the 1960s have offered possible solutions for this approach. An evolutionary algorithm or EA starts with a given ‘population’ – a set of solutions to a problem – which then acts a ‘parents’ to a new generation of ‘children’, passing on their ‘genes’ with minor variations introduced at random. The ‘fitness’ of these ‘children’ in respect to the wanted criteria is then evaluated, and the fittest become parents to a new generation of solutions. In a sense, this is like selective breeding of design solutions. The end result might be a number of good solutions, not necessarily one single optimum. There are several kinds of evolutionary algorithms under the umbrella term: evolutionary programming developed by Lawrence Fogel in the 1960s, evolution strategies introduced by Bienert, Rechenberg and Schwebel in the 1960s, genetic programming developed by John Koza, and the genetic algorithm introduced by John Holland in the 1970s and popularised by David Goldberg.

I. Reichenberg and his colleagues had shown already in the 1960s that it is possible to translate the principles of biological evolution to optimisational tasks in technology. Their take on the technological version of evolution was Darwinian and elective, and worked by integrating into the design process accidents analogous to the mutations in biological evolution and subsequent testing strategies analogous to the selection in nature. Claus Mattheck has also used the principles of accidents and biological optimisation in the strategies of his computer-aided-design (CAD) and computer-aided optimisation (CAO). Mattheck’s optimisation tools, however, are also based on the idea of growth. He has studied the biomechanics and structural optimisation of trees and proposed that the structure of trees follows the ‘axiom of universal stress’: trees add material (grow) to areas of concentrated stress and reduce it in unstressed areas.

English academic and architect John Frazer has tried to develop an architecture driven by the same informational codes that drive organisms. He did this through computer programs that function similarly to DNA, and in an analogous environment. According to Hagan, Frazer’s ambition is to develop buildings that receive information, learn from their mistakes and transmit that feedback into a ‘gene pool’ for future buildings. The idea behind Frazer’s work seems to be based on a Lamarckian view of instructive technological evolution. Another example of the use of evolutionary algorithms in architecture is given by the work of Michael Rosenman and John Gero in the late 1990s at the University of Sidney, where they have studied the formation of house layouts through EA. Their process creates a
Defining Biomimicry

Design Biomimetics • Dollens •

Spiral Bridge based on the sponge *Euplectella*

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A report to the Genetic Architectures Program
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Design Biomimetics: An Inquiry and Proposal for Architecture and Industrial Design

Dennis Dollens

Fig. 23
Images from the formation of a complex surface with the Genr8 tool.

Fig. 24
The sponge *Euplectella* and the leaves of *Tipiana tipu* as an inspiration for the Spiral Bridge by Dennis Dollens and Ignasi Pérez Arnal.
Organic architecture as a concept covers such an array of different manifestations, that is seems impossible and futile to reduce it to a single manifesto. Its roots are in the organic and in the ecological analogies – valuing the inherent ‘rightness’ of nature and the way organisms adapt to and interact with their environment. However, Steadman ventures to find three common characteristics in contemporary organic architecture: first, a method of composition that works from the inside out, from the programme towards external appearance; second, a rejection of the rectangular and the embrace of the curvilinear or non-orthogonal (figure 25); and third, a theme of desiring to live in contact and harmony with nature. The choices of materials illustrate these characteristics: either local and natural materials to reduce consumption of energy in transport and to blend the building into its surroundings; materials that specifically allow the formation of curvilinear shapes; or lightweight structures because of their economy in materials and their resemblance of efficient structures in nature.

Steadman goes on to argue that there are close connections between the ‘new’ organic architecture and sustainable design – a shared concern about global warming, pollution and destruction of the biosphere, rejection of modernity, and integration of green technologies. Although organicity and sustainability often go hand in hand, by no means does it imply that all organic architecture is sustainable, or that sustainable architecture needs to be organic in its morphology.
Fig. 25
An illustrative example of contemporary organic architecture is Sir Peter Cook and Colin Fournier’s Kunsthaus Graz, completed in 2003.
Sustainable architecture, or environmental architecture, or green architecture, or eco architecture, as it is sometimes called, suffers from the fact that its definition is vague at its best. After all, there are many forms of sustainability – environmental, of course, but economic, political and social as well. In the context of this thesis, the term will be taken to mean sustainability in the environmental sense. What this means is that a sustainable approach strives to minimize the negative impact of the building on nature, or if possible, even produce positive effects.

Sustainable architecture does not refer to any specific style of architecture, but rather to a spectrum of sustainable designs ranging from traditional vernacular, to existing styles rendered more sustainable, to environmental determinism. In her book *Taking Shape* (2001), architect and founding director of the department of Research into Environment + Design at the Royal College of Art School of Architecture Susannah Hagan poses the question whether sustainability as a driving force in architectural design will lead the designs towards a certain architectural expression. According to Hagan, sustainable architecture is actually sustainable architecture, "a plurality of approaches with some emphasizing performance over appearance, and some, appearance over performance". One determining feature is that sustainable design works with climate rather than against it (figure 26).

It is difficult and perhaps unnecessary to try to distinguish sustainable architecture from other architectures, or label it as pursuing a certain type of analogy with nature. The ecological analogy might be the dominant analogy drawn, as the objective of a sustainable approach seems to be to accept the role of the built environment in the natural ecosystem of the world. In the pursuit of sustainability, an architect might see fit to resort to design practices drawing from different sources – evolutionary design methods, biomimicry, bioutilisation, and so forth (figure 27). No matter what the chosen design approach, the definitive aim is to produce an environmentally sustainable building. Hagan points out that those involved in sustainable architecture maintain that the distinction is temporary, as in the future all architecture should strive for sustainability.
Defining Biomimicry

Fig. 26
Sustainable system diagram of the Garden School by Open Architecture, with a focus on environmental sustainability with e.g. natural ventilation, cooling and water reuse schemes.

Fig. 27
The Bosco Verticale in Milan by Stefano Boeri Architetti is an example of architecture that can be dubbed both 'green' and sustainable - it utilises trees as a part of the facade to help maintain the conditions of inner comfort, but also to absorb CO2.
It has already been mentioned that the distinction between the concepts of biomimicry and biomimetics are not always clear, even to people initiated in the subject. Biomimetics is a direct predecessor of architectural biomimetics and the approaches are more alike than they are divided. Both approaches mean the abstraction of good design from nature, so why is it even relevant to make a distinction between them? The importance lies in the intentions of designers, and understanding these intentions can make a difference in a collaborative process. When we as architects are working with engineers, other designers and other specialists, we should make sure that we are talking about the same things when we talk about biomimicry or biomimetics. Biomimetics to an engineer most certainly bear a different meaning than biomimicry to a biologist, and that is the hurdle we are trying to overcome by defining both terms in the context of this thesis.

Biomimetics has an emphasis on the ‘engineerability’ of biomimetic research, whereas biomimicry entails a broader scope of ventures with environmental and societal aspects, for example designing a building so that it works as a part of and enhances its local ‘ecosystem’. It was already argued in chapter 4.3, that the ecological analogy is the most relevant to biomimicry in architecture, and helps us understand the difference between biomimetics and biomimicry. Biomimetics focuses on the direct and physical challenges of a design, whereas biomimicry takes into account the indirect and systemic challenges as well as the direct ones. This kind of approach is illustrated in the Seawater Greenhouse project by Charlie Paton. The Seawater Greenhouse project is not just about designing a greenhouse that functions passively with the use of water harvested from the air in arid regions, but also a project that vitalises the immediate surrounding landscape. The project uses the evaporation of seawater at the front of the building to create a cool and humid growing environment for crops inside. This results in lower costs and increased yields. A biomimetic approach might stop here with a successful project. However, with biomimicry thinking, the project can be pushed further. The greenhouse evaporates much more water than it condenses back into freshwater. This humid air is ‘lost’ due to high rates of ventilation to keep the crops cool and supplied with CO2. The higher humidity exhaust air can be used to rehydrate the surrounding landscape, promote plant growth and rehabilitation of the local habitat.

The difference between the two concepts is explained quite succinctly by Pohl and Nachtigall: the term biomimicry implies the direct ‘imitation of life’, whereas biomimetics implies the understanding of biological structures and processes and their comparable technological applications, methods, or procedures. In other words, biomimicry aspires to the imitation of life itself, for example by applying ecosystems thinking into design, whereas biomimetics mimics the ways in which living things function. In this interpretation, biomimicry employs a kind of compositional interpretation of organic analogy, as it takes nature as an example of a ‘wholeness’ and balance one should strive towards, whereas biomimetics works only with a functional interpretation of mostly ecological and anatomical analogies. Biomimicry is a holistic approach which uses biomimetic solutions to achieve sustainability, resilience and a ‘natural balance’.

A biomimicry-driven approach to design includes the incorporation of biomimetic solutions to an array of problems, often technical. To be taken as biomimicry, these solutions should enhance the environmental sustainability of the design and provide positive feedback to the systems the design is a part of. The problems to be solved with biomimicry at large need not be strictly engineering problems, but in
relation with architecture, they most often are. In this thesis, the term biomimetics is used to imply application in engineering problems without regard for sustainability, biomimicry as striving for sustainable solutions with biomimetic innovations in any field of design, and biomimetic as an adjective describing the solutions applied in both approaches. The definitions used in this thesis have continued to evolve throughout the writing process, and are by no means absolute. In future design tasks and architecture practice the concepts will be evolved further, perhaps to a more precise direction. What is important is that an attempt at defining them is made to form a basis for discussion.

Why should one focus on biomimicry instead of biomimetics? That is a choice for each designer to make for themselves, but the arguments for biomimicry are heavier. Biomimicry leads to solutions that are equally ingenious to solutions achieved with biomimetics, but with even more benefits. Biomimicry has the added virtue of sustainability and furthermore, the holistic thinking embedded in the approach serves the architect that is dealing with designs as complex as entire buildings.

The concept of biomimetics is explained here first for two reasons: first, it precedes the idea of biomimicry and second, because the solutions used in a biomimicry approach to architecture are inherently biomimetic. Biomimetics follows the trail of ideas set in motion by Francé’s book *Plants as Inventors*, i.e. to ‘borrow’ evolutionary development from nature by studying structures, materials and systems found in nature and applying the found solutions to technological problems. Biomimetic work and the use of biomimetics in design is itself defined by the methods used, and as such biomimetics is in itself not an independent science discipline. Biomimetics is a term describing an approach to design and engineering, not the actual methods used to achieve a desired solution to a problem. Biomimetics in medicine and material technology for example follow the rules and methods of those fields respectively, biomimetics being the intention behind the work.

The term biomimetics was coined by American inventor, engineer, and biophysicist Otto Schmitt in the 1950s as a portmanteau of biology and technology, and has a wider meaning than the medical and robotic focus of the bionics of Jack E. Steele. Biomimetics is essentially the practise of taking ideas and concepts from nature and implementing them in a field of technology such as engineering, design and computing – for example the development of machines that imitate birds, fish, flying insects or even plants. The applications do not need to strive for sustainability. There is a difference in the interpretation and application of the term biomimetics in different cultural regions, as was touched upon earlier concerning the usage of the German term Bionik (see chapter 5.11, Bionics).

During the twentieth century, as far as building design is concerned, the lead in biomimetics has been in the hands of structural engineers. Norwegian-born engineer Fred Severud saw constructional principles in an array of organisms, which he described in his 1945 paper *Turtles and Walnuts, Morning Glories and Grass*. Severud’s work influenced German architect Frei Otto, who devoted a significant portion of his career to the study and design of tensile structures, largely vast roof structures combining strength with maximal lightness. This interest directed him towards the analysis of natural forms that exhibited these properties. The tensile cable-net roofs of Frei Otto’s pavilions for the 1972 Munich Olympic Games bear a resemblance to
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the web of the *Cyrtophora citricola* spider (figure 29, figure 30). This interpretation of natural analogy, however, might have been later superimposed by others on Otto’s design, and not be the basis for his work. He was also interested in the skeletons and skulls of birds as examples of structures that have evolved towards minimal weight, as well as branching tree-like columns and structures stiffened by the pressure of gases or fluids. Otto’s ‘tree columns’, as applied in the Stuttgart Airport and under some highway bridges, do not look like trees, but nonetheless, have an analogous biomimetic concept of a ‘structural tree’. Before their design, studies were performed on the angles, thickness proportions, and other aspects of tree branches. The optimisation of the functional goal of a column’s dimensions was also studied: what kind of structure could support a given load with over a certain area and have the least amount of mass.

The concept of *Architekturbionik* explored by J.S. Lebedew in his book *Architektur und Bionik* (1983) and translated in this work into architectural biomimetics, is closely related to building biomimetics. The three main components of architectural biomimetics according to Lebedew are:

1. **Functions** with analytical methods and analogy with the natural and built environment.
2. **Building principles** in organic nature.
3. **Design and harmony**.

Lebedew’s description of biomimetics is quite close to biomimicry. First he makes mention of the functional analogies and comparable building principles between nature and the built environment, both essentially biomimetic principles, but he also mentions design and harmony as important aspects. This inclusion of the ideal of the organic takes his definition of biomimetics closer to the biomimicry approach than the definitions of many others. Lebedew’s biomimetics principles are presented in more detail in the accompanying illustration adapted from *Architektur und Bionik* (figure 28).

Biologist Werner Nachtigall has, since he began his interest in biomimetics in the 1960s, always made a difference between ‘technical biology’ and ‘biomimetics in the actual sense’, but fundamentally they are only two different perspectives that connect nature and technology. Technical biology means the investigation of the structures, processes, and evolution principles of nature from the viewpoint of the technical physicist and related disciplines. Biomimetics, however, is an attempt at projecting these base results backwards to technology and to ‘give inspirations for modern solutions better suited for people and the environment’. Architect Göran Pohl began working with biomimetics in the late 1980s, and has collaborated with Nachtigall in biomimetic research. Pohl has been influenced and taught by Frei Otto at the University of Stuttgart, and he sees biomimetics as ‘one design tool among other various possibilities of gaining knowledge within a holistic design process. According to Pohl and Nachtigall, the particular definitions of bionics or biomimetics always reflect the zeitgeist, but the definitions gain more precision through the on-going process of knowledge. From the beginning of 1970s, Nachtigall has defined bionic or biomimetic work as ‘Learning from nature for self-sufficient, engineerable design’.

* It should be noted here that Pohl and Nachtigall have conducted their research in German, and their use of the term bionics carries the same biomimetic connotations as the German Bionik.
Fig. 28
Overview of the basics and objectives of 'Architektur-Bionik', or architectural biomimetics, adapted from J.S. Lebedew in Architektur und Bionik (1983).
In their book *Biomimetics for Architecture and Design* (2015), Pohl and Nachtigall give out the classical definition of biomimetics as follows: “Biomimetics as scientific discipline concerns itself systematically with the technical implementation and application of structural systems, processes, and development principles of biological systems.” The definition was agreed on by the attending technical biologists and biomimetics scientists in a 1993 convention of the Association of German Engineers entitled ‘Technology Analogy Bionics’. Nachtigall has subsequently suggested an alternative definition with broader inclusiveness: “Learning from structural, procedural, and developmental principles of nature to form a positive network of man, environment, and technology”. In this later definition Nachtigall ventures into the realm of biomimicry in spite of how he seems to imply that biomimicry as ‘imitation of life’ would be perhaps inferior to the scientific application of biomimetics. However, to ‘form a positive network of man, environment, and technology’ is directly in line with the objectives of biomimicry.

Pohl and Nachtigall suggest that that the subjects of biomimetics can be summarized by three fundamental disciplines:

1. **Structure biomimetics**, pertaining to issues of substances, materials, prosthetics, and robotics.
2. **Process biomimetics**, pertaining to issues of climate and energy, construction and perhaps architecture, sensor technology, and kinetics and dynamics of machine construction.
3. **Development or evolution biomimetics**, pertaining to issues of neurophysiology, aspects of biological evolution, and corresponding viewpoints of procedural and organisational methods.

These disciplines can be applied to biomimicry as well, as the biomimetic solutions comprising a biomimicry approach fall into these categories. Pohl and Nachtigall go on to point out that even though building and architecture biomimetics fall mainly in the subcategory of process biomimetics because building and design are fundamentally processes, they encroach into structural biomimetics when it comes to building and insulating materials. Development biomimetics play a role if computational evolutionary or growth methods are used in the design process. It can be argued, however, that even though building and design are processes, that it is not these processes that should utilise biomimetics, but rather that the final and built design should utilise biomimetics in its systems and maintenance processes. It is not necessary to utilise biomimetics to optimise the design process itself, but rather that what is being designed.

Just as biomimetics in itself is not a science, but defined by the fields it is used in, so is its definition and boundary conditions. The precise definition of biomimetics is in continuous motion and slightly redefined by each writer and researcher. However ambiguous the definitions are, they help us circle closer to what biomimicry is – in and of itself and as parallel to biomimetics.
Defining Biomimicry

Fig. 29
Above: Frei Otto’s tensile structures for the Munich 1972 Olympic Games.

Fig. 30
On the right: The web of a Cyrtophora citricola, also known as the tropical tent-web spider.
Finally, the route laid out on the map of natural analogies has reached **biomimicry**. Biomimicry follows in the footsteps of **bionics** and **biomimetics**, first used in the field of engineering and subsequently in other fields including material sciences and medicine. The root of the term – as well as the root of the concept – is the same as in biomimetics. Both terms derive from Ancient Greek: βίος (bios) meaning life, and μίμησις (mimesis) meaning imitation, from μιμεῖσθαι (mimeisthai), to imitate, from μῖμος (mimos), actor. Because of this common ideological ancestry, and the chronological precedence of the term biomimetics to biomimicry, defining biomimicry means doing it by differentiating it from biomimetics.

Biomimicry draws on anatomical, ecological and evolutionary analogies: anatomical in the sense of mimicking anatomical features of living organisms, evolutionary in the context of taking evolution as a process which produces ‘fit’ solutions to specific conditions and searching for viable models for emulating these evolutionary solutions through biology and other physical sciences. The ecological analogy plays a large part in the sense of the relationship between the building and its environment, and in the way in which a building works as its own ‘ecological’ system, and finally, in the role a building project might play in the larger ecological system of our planet. All in all, biomimicry is a functional analogy – it endeavours to mimic the way nature works, not the way it looks. In her book *Architecture Follows Nature* (2013), Architect Ilaria Mazzoleni argues that in the field of architecture, biomimicry has only been used since the early 2000s, reconsidering biomimetics as applied to architectural design. However, the legacy of biotechnics and biotechnique in architecture should be acknowledged for their influence, as well as Ban-Bionik and Architektur-Bionik as direct predecessors of contemporary architectural biomimicry.

In order to make a more clear distinction between biomimetics and biomimicry, it is essential to include views from outside the fields of engineering or architecture. Successful biomimicry needs input from the life sciences, and they should be included in the definition of the term as well. Architects and engineers alone cannot claim expertise on a field that is so inherently interdisciplinary. Experts of life sciences carry out the research on natural role models, and the results of that research should be abstracted and implemented with scientists and designers together. American biologist and biomimicry advocate Janine Benyus has been vital in the popularisation of biomimicry through her writings and work with the Biomimicry Institute, Biomimicry 3.8, and Asknature.org. She stresses an ecological standard, ‘nature as measure’ as the basic dogma of biomimicry, and this illustrates the fundamental difference between biomimetics and biomimicry. The biggest difference between biomimetics and biomimicry is fundamentally an ideological one: the advantages of sustainability – environmental or societal – in a design cannot always be reliably measured nor justified in terms of economical benefits.

Benyus defines biomimicry in the following ways:

1. **Nature as model.** Biomimicry is a science that studies nature’s models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf.
2. **Nature as measure.** Biomimicry uses an ecological standard to judge the ‘rightness’ of our innovations. After 3.8 billion years of evolution, nature has learned what works, what is appropriate, and what lasts.
3. **Nature as mentor.** Biomimicry is a 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.
These points further clarify the differences of biomimetics and biomimicry. Biomimetics uses nature as a model, but the approach does not concern itself with the two other aspects. Biomimicry, however, is about taking lessons from natural solutions, but also judging what should be designed with them according to an ecological standard (figure 31). The last point, nature as mentor, drives home the ideological aspect of biomimicry: a humble and appreciative curiosity towards nature and its phenomena. Biomimicry means working with nature by learning from it, not against it, nor simply by getting something out of it.

Biomechanics researcher Steven Vogel has described the ‘bioemulation’ of biomimicry as essentially: “Making better widgets by copying nature”. He also offers critique of biomimicry in his book *Cat’s Paws and Catapults* (1998), pointing out that most of the allusions to successes in biomimicry are merely instances of recognising elements of mechanical commonality. For example, he disassembles and refutes the commonly cited biomimetic story of the structure of the *Victoria amazonica* water lily being the model for the roof structure of Joseph Paxton’s Crystal Palace (figure 32). It would seem that much of what has been dubbed biomimetic has been done so in retrospect. In many cases it is most a question of bioinspiration, the ingenuity of the designer and the human need to create a story, to find allusions and meaning in coincidental or symbolic resemblance. More of the quite accurate criticism towards biomimicry will be explored in chapter 8, *WHAT is successful biomimicry?*

Biomimetics researcher Julian Vincent’s definition of biomimetics (and subsequently biomimicry solutions) has been quoted by architect Michael Pawlyn as “the abstraction of good design from nature”; while for Janine Benyus it is “the conscious emulation of nature’s genius”. These two quotes vocalise essentially the same thought, though Benyus seems to do it with a more elevated attitude towards the perceived inherent goodness of nature. Pawlyn himself defines biomimicry (and biomimetics, a term he uses rather confusingly synonymous with the former) as “mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions”.164
In this thesis, *biomimicry* is defined as a design approach of taking phenomena, processes, and systems found in physical nature, analysing them, and applying the found principles to corresponding performative design problems. Phenomena and systems in this case include, and are not limited to, materials, structures, circulation of air and water, striving for economy, and closed systems. Simply put, *biomimicry* means using nature, and the endless array of solutions optimised by evolution as a ‘toolbox’. A biomimetic design approach strives for the most optimal solution in terms of performance and material ecology. In the literature about biomimicry, evolutionary design methods are sometimes included in the toolbox of biomimicry. In this thesis they have been excluded from that category, as they would in themselves deserve a more profound treatment that can here be given, and as a whole follow a different strand of natural analogy. In architecture, biomimicry can be used to emulate environmental and climate-adaptive systems found in nature, such as the natural ventilation system of termite mounds. Other ways of drawing a biomimetic lesson might be to analyse physical phenomena, such as soap bubbles, or strategies and adaptive systems for maintaining homeostasis in natural organisms, or metamorphoses and hybrid materials.

Why should biomimicry be used in architecture, then? And how, if we can be persuaded by the positive potential of the approach? The next part of this thesis, *Designing with biomimicry*, will attempt to answer these questions.

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**Fig. 32**
The interior of the Crystal Palace, not inspired by the water lily, but a feat of modern engineering.
Defining biomimicry, references

[4] Ibid., p. 11.
[10] Ibid., pp. 18–19.
[12] Ibid., pp. 8–9.
[16] Ibid., p. 10.
[17] Ibid., pp. 16–18.
[18] Ibid., p. 51.
[21] Ibid., p. 39.
[22] Ibid., p. 12.
[27] Ibid., p. 55.
[28] Ibid., pp. 55–56.
[31] Ibid., pp. 56–57.
[33] Ibid., p. 147–148.
[36] Ibid., pp. 120–126.
[37] Ibid., p. 76.
[38] Ibid., p. 78.
[39] Ibid., pp. 97-98.
[41] Ibid., p. 23.
[52] Ibid., p. 25.
[54] Ibid., p. 39.
[58] Ibid., pp. 41–43.
[59] Ibid., p. 69.
[60] Ibid., pp. 27–30.
[63] Ibid., pp. 46–47, 49.
[64] Ibid., pp. 51–53.
[65] Ibid., p. 47.
[66] Ibid., pp. 49–50.
[67] Ibid., p. 51.
[68] Ibid., p. 241.
[69] Ibid., pp. 52–53.
[70] Ibid., p. 241.
[71] Ibid., p. 76.
[72] Ibid., p. 78.
[73] Ibid., p. 99.
[74] Ibid., pp. 97-98.
[75] Ibid., p. 99.
[76] Ibid., p. 110.
[79] Ibid., p. 205.
[80] Ibid., p. 125.


[153] Ibid., p. 5.

[154] Ibid., p. 5.

[155] Ibid., p. v, 5–6.

[156] Ibid., p. 1.

[157] Ibid., p. 6.

[158] Ibid., p. 6.


[161] Ibid., p. 0 (preface).


[163] Ibid., pp. 250–257.


Designing with Biomimicry
Once we have arrived at what biomimicry means in terms of emulating nature, and its ideological context and orientation, it is time to turn one's attention towards its possible utilisation in architecture from a design perspective. How to design with a biomimicry approach, and what constitutes as a biomimetic building or design? These are the questions that this part of the thesis aims to answer by expanding on the concept of biomimicry and discussing possible design strategies. In this thesis, the term architecture is used very broadly to include aspects of our built environment ranging from buildings to landscape architecture and structural engineering, without an artificial division into separate fields. As one of the key elements of a biomimicry approach is a multifunctional and interdisciplinary take on the design problem, this holistic take on the design of the built environment is a form of biomimicry in itself. A holistic approach in architecture ties into ecosystems thinking: you cannot treat the building separately from its environment. This environment means the site, the climate, and the social, ecological, and political surroundings of the project. The best solution will be reached when a building is seen as a factor in this complex network.

As established in the first part of this thesis, architects and designers have drawn inspiration from natural analogies throughout history, sometimes as mere shapes, but increasingly, to suggest ways of achieving function. Hagan suggests that the division between nature and culture is becoming increasingly blurred, because culture is able increasingly to understand and imitate the operations of nature. This imitation is very different from mimicking the way that parts of nature look, or are organised.166 The underlying assumption in biomimicry is that evolution has driven organisms to implement functions that are more efficient than man-made systems, and this is why we would do well to learn from them. This is in part because man-made technologies are hindered by the need to understand a principle or phenomenon before it can be implemented in a functional design. However, as Julian Vincent points out, biology has no such limitations.167 What does this difference mean for the architect? In man-made technologies, we need to first understand the basic principles of a technology, then imagine how they could be used, and only when we are certain that we understand all aspects, can we implement the theorised principles in a design. With biomimicry, however, the process takes a shortcut: we can take a strategy from nature, accept that it works, and then study it enough to understand the principles to be abstracted and implemented in a design. Biomimicry means not looking for solutions in a library of theoretical knowledge, but instead in a collection of proof-of-concept models – what the biomimicry student needs to do is figure out how to replicate the desired functions of those natural models with a different set of materials and boundary conditions.

In nature the only criterion for successful implementation is the ‘survival of the cheapest’.168 This means that superfluous use of resources does not aid in the survival of the organism, and structures are not formed to withstand large failure margins. Resources are used wisely, however to tolerate deviations from the norm and to promote resilience. In architecture, striving for the ‘cheapest’ solution can be interpreted as striving for the most optimised solution for example in terms of use of material, structural efficiency or ecological footprint of the project. By stealing innovations from nature, we can design in a way that optimises the use of resources, results in sustainable and resilient designs, and can produce interesting spatial experiences.

The need for sustainable architecture and resilient solutions is in this thesis taken as a matter of course and a goal in itself without a need for further argumentation. The changing climate challenges we face on our planet and the need to reduce pollution...
and emissions is constantly driving sustainability as a standard in architecture. Since nature has created and optimised products whose ‘marketability’ has been tested and whose ‘product profile’ has been honed and configured for their niche, it would be foolish not to use these solutions in applicable situations in man-made designs. After all, natural organisms have had to evolve in response to a multitude of needs to maintain homeostasis: envelopes, thermoregulation, energy production, structure, enclosure, unfolding, transportation, movement, and growth. All these needs have to be met in response to the laws of physics and chemistry, and usually with the additional demands for accommodating growth, reaction to the environment, and utilisation. These same laws apply to the built environment, even though the architect must tackle the challenge of creative implementation and architectural expression as well.

One could pose the question: Why not simply base the performative principles of architectural designs on the well-established and documented laws of physical sciences? Steadman argues that biological models serve as conscious inspiration to the engineer or designer only when there is no generalized theoretical knowledge concerning the problem or area at hand. Vogel has also pointed out that the success of biomimicry depends inversely on how well the underlying science of a context is understood. If the underlying science is well understood, copying produces at best narrowly targeted, specified items – whereas when the knowledge of science is weaker, copying can generate devices of broad utility. It is precisely this relationship between little knowledge and large potential that plays in favour of biomimicry especially in architecture. It is unrealistic to expect any one architect to master detailed theoretical knowledge concerning all the technical and design problems in a given task. Therefore it is fitting for the designer to seek a predecessor in nature, an instance where a certain problem has already been solved, and through that example to deepen their knowledge on the matter, by looking up possible further research or information.

By pursuing biomimicry and biomimetic solutions in the design process, the architect can happen upon innovation that would not otherwise have presented itself because of the extensive scientific knowledge required to understand the underlying principles. The architect is the ideal biomimicry student, with a wide scope of curiosity and a drive for innovative solutions.
Though biomimicry promises innovations, it is only when used with careful consideration and insight that the promise holds true. Biomimicry requires honesty and humility in learning from research and life sciences. In *Cats’ Paws and Catsapults*, Steven Vogel gives three prerequisites for a successful biomimetic example:  

1. What is provided by nature is the idea, the inspiration or the strategy, not the details or tactics used by humans to implement the strategy.
2. Success depends inversely on how well the underlying science is understood.
3. The differences between the two technologies (natural and human) must be understood and exploited – where one technology operates in what is normally the domain of the other, emulation holds promise.

The first prerequisite means that the inspiration from nature must be analogical, i.e. based on the concordance of functions. Moreover, no function or strategy can be directly copied without taking into consideration differences in materials and scales between the natural predecessor and biomimetic design. As mentioned earlier, the principle of similitude presents a challenge, as some phenomena only function in a certain scale – for example the water-harvesting potential of the fog basking beetle’s shell, which is a result of microscopic bumps in the surface of the shell, surrounded by hydrophobic material. The beetle’s water harvesting strategy and how it has been used to inspire architectural solutions will be explored in chapter 9.4, *Water management*.

Furthermore, to achieve success in biomimicry, a certain level of abstraction needs to be achieved in the process from inspiration to implemented design.

Nachtigall reduces the approach of biomimetics to a three-step process: research – abstraction – implementation. The three steps, though simplified, give a good picture of what the key elements of a biomimicry process are. Research and implementation are not enough, but it is paramount to formulate the analogies at an appropriate level of abstraction. The chosen level of abstraction should enable the capture of the desired characteristics of the biological system from which inspiration is being taken, while trying to avoid redundant complexity in the implementation. It should also be noted that biological systems are highly integrated and perform multiple functions, and isolating a single function for imitation requires careful consideration of the interconnectedness of the original system. A bird’s wing, for example, has additional functions in addition to providing lift for flight including thermoregulation and sexual signalling – not taking these additional functions into consideration in the abstraction of the system can lead to unnecessary complexity in the technical implementation. The lesson articulated here is an important one: nature works in interconnected systems, where one part cannot be isolated from another - the solutions found in nature are not a pick’n’mix sampling to be arbitrarily combined without careful study and consideration of the desired outcome.

The second condition – that success is inversely dependant of how well the underlying science is understood – touches upon why biomimicry might be a valuable tool especially for architects. Vogel argues that if the underlying science is of a phenomenon is well understood, copying produces at best narrowly targeted, specified items, whereas when the knowledge of science is weaker, copying can generate innovations with a broader scope of utility. As argued in the previous chapter, this is beneficial for architects as they cannot master any one scientific field in detail, but are experienced in abstracting concepts and their potential in the creation of space. Vogel also argues, that asking how would nature solve a specific function is a naïve approach to biomimicry. His argument is that the closer a
question is defined, the less likely one is to find a robust answer because nature and technology are too different. It is not, however, the basic formula of the question 'how?' that is problematic, it is the range of solutions we are willing to include in the question. For example, if we want to design a building envelope that reacts to changing ambient conditions, we might be tempted to think that the envelope has to be kinetic, and look for natural examples of movement. However, there is a difference between asking 'How do plants move?' and 'How do plants react to changes in their environment?'. By beginning the biomimicry process with a question that includes a wide array of strategies enables us to be free from presuppositions and approach the problem with a truly open mind. Only then can we find solutions that are innovative and outside our initial conception of the problem and its possible solutions.

The third prerequisite Vogel points out is that the differences between natural materials and structures and their man-made analogues must be understood. Nature is typically wet, tiny, non-metallic, non-wheeled and flexible, while human technology is usually the opposite: large, dry, metallic, wheeled and stiff. There is potential in exploring how and why nature produces flexible joints instead of hinges, but it does not mean that a flexible solution is always superior.

Vogel also warns against blindly taking nature as the golden standard of design. In nature, fundamental innovation comes hard, and once achieved, it is hardly ever spread beyond a single lineage. The adaptive advantages gained through evolution cannot spread laterally. This same principle is mentioned by Jan Knippers and Thomas Speck in their article Design and construction principles in nature and architecture (2012), where they explain that living beings carry an ‘evolutionary burden’ because...
evolutionary innovations always build on inherited structures and their respective functions. This inherited structure and the requirement for successful ‘functionality’ of the organism during all phases of evolution confine the potential of natural selection as an optimizing agent.\(^7\) Once an organism is adequately adapted to its environmental conditions to survive, there is no more evolutionary push for further optimisation. It was already mentioned in chapter 5.7, *Theories of technological and craft evolution*, that the idea of evolution having any goal or direction is a fallacy. In nature, things function only just in the conditions they are attuned to, they do not overperform. It is the survival of the cheapest, not the most elegantly fine-tuned.’

Knippers and Speck provide another set of guidelines for successful biomimicry. Whereas the aforementioned prerequisites were meant for a successful design process, the following focus on the characteristics of a successful biomimicry design. According to them, an important characteristic of natural systems is a ‘multi-layered, finely tuned and differentiated combination of basic components which lead to structures that feature multiple networked functions’. Design principles derived from this axiom could be classified as follows:\(^7\)

- **Heterogeneity:** Natural constructions are characterized by a geometric differentiation of their elements, as well as by local adaptations of their physical or chemical properties.
- **Anisotropy:** Many natural constructions consist of fibre-reinforced composite materials.
- **Hierarchy:** Biological structures are characterized by a multi-level hierarchical structure from nano- to macro-scale. Each of the levels consist of similar molecular components, but give rise to different and, to some extent, independent functional properties.
- **Multifunctionality:** Botany fibres simultaneously serve mechanical and diverse physiological functions.

Again, we cannot leave the definition of successful biomimicry to the realm of only engineering, architecture or biomechanics, if we are trying to understand the concept beyond ‘engineerable’ biomimetics. Biomimicry 3.8, a biomimicry consultancy founded by Janine Benyus and biologist and ecologist Dayna Baumeister, defines the goals of successful biomimicry around the concept of ‘Life’s principles’. The principles are obviously not fine-tuned for architectural design, but complement nonetheless in an interesting way Vogel’s and Knipper’s and Speck’s engineering-oriented theses. The basic concepts of ‘Life’s principles’ (figure 33) are as follows:\(^8\)

- Adapt to changing conditions.
- Be locally attuned and responsive.
- Use life-friendly chemistry.
- Be resource efficient (material and energy).
- Integrate development with growth.
- Evolve to survive.

These aforementioned concepts should be implemented under the Earth’s ‘operating conditions’ of sunlight, water, gravity, dynamic non-equilibrium, different limits and boundaries, and cyclic processes.\(^8\) The addition of cyclic processes to the prerequisites of successful biomimicry ties the process in with ecosystems thinking, and will be included in the Biomimicry Design Cycle to be introduced in chapter 10.1.

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Instead of giving clear instructions about what makes for successful biomimicry, it seems easier to warn against pitfalls in the approach. Possible reasons for the failure of transferring ideas from nature to technology and design could be superficial research, no information from life sciences, an unimaginative approach or trying to copy a phenomenon that is not scalable. A key element in avoiding these pitfalls is a multidisciplinary approach to the design process. The architect should consult specialists in life sciences to ensure that the strategies and phenomena they are trying to abstract are fully understood, and so that the analogy can go further than superficial mimicking. The potential of biomimicry, however, is vast if one does not expect the impossible and keeps an open mind.

It has now been established what biomimicry is and why it could be useful for architects, but the question remains where to actually apply it. What are the aspects of building design that could benefit from it and the architect could be inspired in designing? Architect Michael Pawlyn discusses in his book *Biomimicry in Architecture* (2011) the different areas in which a biomimicry approach could be utilised. He has worked extensively with a biomimetic design approach first in his work with Grimshaw Architects and subsequently as the director of Exploration Architecture Ltd, where the focus is on sustainable projects with a biomimicry approach. The proposed categories are comprehensive and take into account the sustainability and ecosystems thinking focus of biomimicry:

- **Structures**
- **Materials**
- **Zero-waste systems**
- **Water management**
- **Thermal control**
- **Energy management**

What all of the proposed areas of application have in common is a pursuit of resource efficiency and economy, and optimisation of structures and function. This could be described as an attitude of ‘survival of the cheapest’, where ‘cheap’ means the satisfaction of function with optimal but not superfluous means. However, in addition to the utilitarian aspects of applying biomimicry, biomimicry could and should also be used to enhance architecture and the experience of space itself. Architecture is more than the solution to minimum comfort in built form; it is also about expression, embedded meanings and aspirations, identity, and at best, art.

When applying a biomimicry approach to the aforementioned areas, the solutions should be viewed through the lens of architectural expression. Here one could take inspiration also from how nature works with:

- **Light**
- **Enclosure and Patterns**

These points of emphasis are decidedly architectural but not in any way contradictory to the aforementioned categories. The handling of light in architecture has to do with thermal control and energy management, but also architectural expression and the experience of space. Patterns and enclosure might deal with structures and materials, but more importantly also the experience of space.
The next chapters will focus more on each of the proposed categories biomimicry use in architecture. All of the aforementioned aspects have a different presence in the design, production, and maintenance of buildings, and in the following chapters these themes are discussed with an emphasis on biomimicry, not merely biomimetics. The categories of light, enclosure and patterns have not been specifically addressed, because it is encouraged to keep these concepts simultaneously in mind whenever focusing on the functional and utilitarian aspects of design. The examples given in each chapter range from describing how aspects of each category work in nature to examples of how these principles have been an can be applied in architecture.

Before venturing further, it should be noted that as Pohl and Nachtigall have pointed out with merit, using biomimetic (or biomimicry) in design is not in itself an independent discipline, but defined by the methods used. This means that the examples given in the following chapters, though comprehensive, are by no means an exhaustive catalogue of the how, why, and where biomimicry should be used in architecture. There are as many possible innovations as there are architects and design tasks. The examples are meant to inspire and give an overview of the possibilities of the approach.

According to Julian Vincent’s often-quoted rule of thumb, in nature “Materials are expensive, design is cheap”, whereas in the man-made world “Materials are cheap, design is expensive”. This is why biological materials are lightweight and durable, and a carefully considered design might need half the amount of material than a more robust one and still be more durable. The most important considerations regarding structure with a biomimicry approach is the optimisation of the used material with regard to the specific instance of structure, the hierarchical nature of both the structure and the material, and that natural structures tend to be flexible and resilient, whereas man-made are structures are usually rigid.

Architecture and civil engineering have a very different approach to structures when compared to nature’s approach. Knippers and Speck point out that in architecture and engineering, there is a division between ‘material’ and ‘structure’, whereas in nature – from macroscopic organisms to molecular components – each structural element is made up of smaller sub-structures consisting of similar building components, making up a structural hierarchy on usually five to eleven levels that can span up to twelve orders of magnitude. Therefore, in natural organisms, a separation into ‘material’ and ‘structure’ categories is not possible, nor is it desirable. In this thesis, however, structure and material are discussed as two overlapping categories. This is because of the conventions of building design and materials and the leap in scale between the architectural structure and the material structure.

Knippers and Speck go on to argue that the same indivisibility as with the terms ‘material’ and ‘structure’ applies to the terms ‘structure’ and ‘form’ as well. The various functions of for example a thermal envelope, spatial separation, building services or load transfer, are assigned to different components. This results in an architecture in which the load-bearing ‘structure’ and the space shaping ‘form’ of the building are functionally separated. In natural structures, however, the basic building components not only support the structure but also ‘carry substances that catalyse chemical reactions and recognize molecular signals’. The ‘form’ is the result of functional requirements that are met by the ‘structure’, which cannot be divided
Natural constructions consist of only a few basic components, which are geometrically, physically and chemically differentiated, and in this respect, fundamentally different from most architectural constructions, where material and functional components are highly differentiated (e.g. steel for the structure and glass for the envelope).

The way in which the use of material is optimised in nature is clear in cases where the whole of the structural element is made from the same material. Some examples of simple transformations of materials into structural elements found in nature are hollow bones, plant stems and feather quills: all these tubular elements show a principle of optimising a structure by removing material from areas close to the neutral axis and placing it where it can take more stress from bending. A specifically illustrative example is that of the bamboo: the great height that some species have accomplished (40m) is due to the strengthening of hollow section elements through regular nodes that act like bulkheads (figure 34). This shows the advantages of using material only where it is needed to achieve an optimised structure. Curves and folds are another significant way for plants to sustain the stiffness of bigger elements, e.g. leaves and thus create more surface area for photosynthesis. One example is the Southern Magnolia, which presents a fold along the midrib and each half of the leaf is curved. Both the curve and the fold are contributors in the leaf’s stiffness. Structural applications of a folding technique in architecture, however, are not straightforward. They require for example a large spanning width of the panels of a folding structure or additional folding elements, such as thermal insulation. Because of this, thicker folding elements should be produced, but they are limited in their ability to be folded together. Other structure types where inspiration could be found in nature are tension structures and pneumatic structures – here the analogy must be made carefully, however, as a spider’s net or a swelled-up plant cell cannot be scaled up to building scale without significant issues in the weight of the structures.

Another example of analogous structures are in nature and technology are dome-forming node-and-rod structures. They are composed of rod members (pressure
and tension rods) and nodes (joints), and an optimised structure works with the least possible amount of members. It should be noted that man-made technical and spherical mesh works are rigidly arranged, whereas a natural spherical form, e.g. that of radiolaria, must be able to morph and adjust. Another analogy can be drawn from the structure of the radiolaria of the Acantharea group and self-supporting tensegrity structures (figure 35). In Acantharea, tension elements are braced with radial, compression-resistant spines, which can be augmented. It has an outer membrane that is the biological equivalent to the tension elements in tensegrity structures. These analogies seem compelling, but it should be taken into consideration that a spherical form in man-made structures is not as optimised as it is in radiolaria, which are zooplankton with intricate mineral skeletons living in the oceans. The omnidirectional hydrostatic pressure the radiolaria live under presents different structural demands than the directional pull of gravity on land.

The difference in the flexible building style in nature and the rigid way people build in order to guarantee structural load-bearing qualities is evident in the case of the glass sponge. The tube-like glass-sponge Aulocystis spec. features nearly rectangular lattice structures in its walls. The structure consists of membranes in which star-shaped spikes are suspended: in the sponge’s process of growing, the spikes often shift and re-orient themselves before fusing together. This kind of structure of flexibly connected members is in itself not stable. Architect Frei Otto experimented with similar orthogonal lattices, but in his design the nodal points had to be formed as rigid nodes to ensure the stability of the system. Pohl and Nachtigall point out that in contrast to technical structures, material in biological structures is accumulated in locations where bending stresses occur. The stresses themselves are functionally used and at the same time dissipated by the growth processes they have induced. Claus Mattheck, who has done extensive work on the biomechanics of trees, has proposed that biological forms follow the ‘axiom of universal stress’. This means that in locations where there is concentrated stress in the structure, material is built to evenly distribute the forces, whereas in unstressed areas there is no material.

Drawing analogies between natural and technical structures is not simple, however. As the ‘structural intention’ in an organism can be thoroughly different than a technical reading of it might suggest: nature works in complex interconnected systems and one ‘structural’ part always has other roles as well. Biological structural types and technological structural types should be compared with caution, as discussed in the previous chapter with the example of a bird’s wing’s functions. Knippers and Speck have formulated model concepts that should be taken into consideration when drawing analogies from biological structures to technical structures (keywords in parentheses underline the concepts that should be newly considered):

1. Biological structures cannot be described by ‘pure’ technical-structural types. (complexity?)
2. Biological building processes simultaneously proceed according to laws of mechanically antagonistic structural principles. (compromise solution?)
3. In biological building processes stable forms can only be approximated. A biological structure is, therefore, always only efficient under completely certain circumstances. (instability?)
4. In ontogenesis, chronological and already ‘anticipated’ partial problems are solved, which in each case determine the conditions of the following development step. (form–function adaptation?)

Biomimicry in Architecture
The structureFIT process works in three phases to find a satisfying structure: problem setup, exploration and refinement. This allows for the designer to consider structural optimisation with regards to other design criteria, such as architectural expression.
Pohl and Nachtigall go on to argue that the comparison of biology and technology could yield insight to structural form: Because natural structures need to grow, they work with ‘preformed deviation’, which means that they must allow slight instabilities and accidental variations. This means that optimisations in biological structures do not require that structures have great margins of safety. In contrast, nature produces structures that are sensitive to variations and still precisely and only just efficient. The tensioning from the growth process in living structures is simultaneously used to stimulate this process and results in a network of building processes, function, and adaptations to specific structural loads. Understandably, these kinds of self-organizing processes would be extremely difficult to use in the scale of buildings, but could inspire experimental constructions or self-correcting structures. Of course, a self-organising process might be simulated with software rather than the actual physical building process. This is implied in the properties of evolutionary algorithms and optimisation software. The advancements in building technology and material sciences also allow for architects to experiment with structures and assembly systems that would not have been previously possible. Building parts do not necessarily have to be modular or joined in the simplest way possible, but each part can be highly specific to its location and role in the structure. In a modern computer-aided manufacturing techniques it is not important if a milling geometry of a joint is standard or not. Contemporary lattice shells, for example, can adapt to almost any geometry.

The idea of optimising structures to achieve better load-bearing qualities with high resource efficiency is not unique to the biomimicry approach, but still a relevant one, as the principle for it can be observed in everywhere in nature. What can be achieved with biomimicry are leads toward structural solutions that need then to be further examined to account for the problem of scaling. With the use of computers and 3d-modeling, optimisation tasks that in nature are done by evolution and growth can be done with different structural optimisation software, e.g. SOLIDWORKS, iSIGHT, DOT, Matlab (fmincon), Ansys, or MSC. Visual Nastran FEA.

What needs to be considered, however, is whether the pure optimum of a structure is what the architect is seeking, perhaps at the cost of architectural values. Professor Caitlin Mueller, currently running a research group called Digital Structures at MIT’s Building Technology Program at the Department of Architecture, has done some interesting work in meshing together the computational optimisation of structures and the architect’s artistic choice. The research group’s first interactive design tool, structureFIT, is a free web-based platform for exploring the structural design of planar trusses, which allows for designers to make changes to a selected design and observe performance implications in real time (figure 36). A piece of software called Stormcloud, in beta as of the writing of this thesis, is a plug-in for Rhino and Grasshopper to enable the flexible interactive evolutionary exploration of optimised structures and their architecture.
Fig. 37
On the right: The laminated structure of nacre, the material of the Abalone shell.

Fig. 38
Below: Hierarchy in material and structure is the source of resilience in nature. The hierarchical structure of the Euplectella aspergillum, also known as the glass sponge or the Venus flower basket, showing up to 8 levels of hierarchy.
Hierarchy in biological structures was already discussed shortly in the previous chapter. It was explained that it is this hierarchy that makes the separation from ‘material’ and ‘structure’ in nature not possible. It also means that hierarchy is one of the most important aspects in materials hierarchy. Other interesting aspects include the recyclability and manufacturing processes of natural materials, and the way materials in nature react to changes in their environment due to their inherent properties.

Robert Allen describes material hierarchy in *Bulletproof Feathers: How Science Uses Nature’s Secrets to Design Cutting-Edge Technology* (2010): “Hierarchy is a direct outcome of self-assembly in biology, itself driven by information from molecular ordering. The versatility of a material is enriched by more structuring at each level of hierarchy, so that adaptability increases with the number of levels.”\(^{199}\) The resource efficiency also increases with each level of hierarchy: as each structural component is in itself an optimised component made of optimised components at a different hierarchical level. Hierarchy delivers benefits in stiffness and fracture control, which is achieved through interfaces between levels of hierarchy.\(^{200}\) A good example of the interconnectedness of structure and material, and the merit of hierarchy, is the abalone. Its shell works as a composite made of polygons of aragonite bonded together with a flexible polymer mortar. The end result is a material stronger than any man-made ceramic, and shows the advantage of a hierarchical material: the shell consists of hard ‘platelets’ that if stressed over the limit, crack individually without affecting the neighbouring platelet (figure 37). In this case, the polymer acts as an interface with a certain degree of flexibility and helps spread concentrated loads over a large area of a shell.\(^{201}\) Another, often mentioned, example is the *Venus flower basket* (*Euplectella aspergillum*), also known as the glass sponge (figure 38).

In nature, there is no waste. All matter is part of an endless cycle of use and re-use by organisms and natural processes. Pawlyn argues that our use of resources can be characterised as linear, wasteful and polluting, whereas in nature resources are maintained in closed-loop cycles. He goes on to argue that even if we don’t limit ourselves to the use of organic materials, we could ‘apply some of the resource stewardship found in nature to those metals and minerals that are safe to use’.\(^{202}\) There is a lot to learn from the material processes in nature, as they are economical in their use of base material and produce nothing that could not be further utilised after its initial use is over – everything is, for lack of a better word, ‘recyclable’. This is an important biomimicry lesson to be taken from nature to architecture: to promote using mixtures of materials and assemblies of components that are, after their current lives, recyclable in an economically feasible way. Pawlyn gives a few examples of building products where this is not the case: composite floor decks and double-glazed window units. In the floor units, concrete is poured into profiled steel sheets that are so textured that the separation of concrete and reinforcement would only ever be highly unlikely and not practicable; with the glazing units, the glass is often coated with a low-emissivity layer and then bonded together along with butyl, silicone, aluminium and desiccants, making it improbable that those resources could be recovered after their initial use.\(^{203}\) In addition to being fully ‘recyclable’, nature works with materials that are easy to manufacture and recycle in ambient conditions.\(^{204}\)

There might be some solutions to the aforementioned problem of recyclability based on biomimicry. By making insulated glass units out of spectrally selective glass based on the light refracting microstructure of a *Morpho* butterfly’s wing one could avoid using coating that contaminates the recycling process.\(^{205}\) Other applicable
innovations could include this kind of ‘biological colour creation’ for products that are usually coated with paint. Biomimicry has proven a successful innovation method specifically in material technology, and this effect could trickle down into architecture at least in the form of innovative building products.

Many natural materials react to changes in their environment without electronic sensors, processors or actuators – the material itself is the sensor and actuator, and there is no need for a processor. These include, but are not limited to, materials that react to moisture, different types of radiation (including light) and heat. Some of these materials and design processes they have inspired will be further presented in the case studies in the next part of this thesis. Reactions to environmental changes also include growth and repair processes, which are more difficult to implement in architecture. Some innovations have been achieved, e.g. in self-repairing concrete and additive manufacturing.

**Fig. 39**
The Mine the Scrap software will scan the scrap pieces available and adapt the structure according to the preferences of the designer.
9.3 Zero-waste systems

It was already argued in the previous chapter that in nature, there is no waste, as all matter is a part of cyclical re-use processes. The word ‘waste’ can be read in two different ways, Pawlyn points out. One reading dismisses waste as worthless material and the other reveals its possibility as a lost opportunity. In this chapter, the strive towards zero-waste systems akin to natural ecosystems means both systems that create no waste and let nothing go to waste (the two expressions could be argued to mean the same thing just looked at from a different perspective). This relates to a shift in architecture and in the way we use resources altogether from a wasteful linear way to a closed-loop model by introducing materials that can be recycled and reused. This might mean that the system boundaries of a building and its building process need to be widened to include material production processes and the handling of maintenance and possible future disassembly.

Another way to apply biomimicry in terms of zero-waste is to ‘use what is abundant’. In nature, opportunism is a virtue – if there is an unexploited resource in an ecosystem, an organism will soon arrive to inhabit that niche. So too, could architects work with local resources, using materials characteristic to the site, or even waste materials. This might seem a far stretch to be called biomimicry and not just common sense and economical design instead. Here it is argued that this is biomimicry as an interpretation of ecosystems thinking. By using locally abundant materials (or waste), the waste created in the production of building elements and their transportation is minimised: only the amount of material to be used needs to be harvested, be it stones from a local quarry or found sheets of corrugated metal; this material can be then refined close to the site. This, of course, is irrelevant, if the refinement process of the materials to building components is not done locally. As Pawlyn puts it: “Biological organisms rarely bring building materials over long distances to the site; instead they bring evolved ingenuity to the site and create structures with what exists there.” A plant cannot move from its location to a place with better soil – it evolves to make the best out of the environment it is in. Some interesting research has been done by the design studio Certain Measures on the potential of cataloguing pieces of scrap material to allow them to be re-used as building material with added precision. Their installation Mine the Scrap (2016) is a data driven process that designs new structures algorithmically generated from existing scrap (figure 39). Using computer vision and construction automation is used to address the need to convert waste into a resource.

Furthermore, if ‘waste’ is seen as an underutilised resource, then its meaning can be expanded to include different collateral and perhaps even unwanted features in any given design. Introducing system feedback loops can provide valuable benefits when thinking of zero-waste systems, as well as energy and water management. The principle of systems feedback loops is briefly explained as part of the Biomimicry Design Cycle in chapter 10.1.

9.4 Water management

Water management is not necessarily one of the things one would think is inseparably linked with architecture, but the more arid the local climate, the more important it becomes. Climate scientists predict that much of the world in tropical latitudes will experience temperature increases and reduced rainfall, whereas other parts of the world are likely to experience increased rainfall. Water management cannot be completely separated from the issue of thermoregulation, as quite often an arid climate is linked with high solar gains, and managing unwanted heat gains...
Fig. 40
The Namibian fog-basking beetle showcasing its water harvesting skills.

Fig. 41
A rendering of the yet unbuilt Las Palmas Water Theatre. Like the Seawater Greenhouse projects, the Water Theatre utilises renewable energy in various ways, using a combination of the sun, the sea and the atmosphere to create cooling and fresh water.

Fig. 42
The Seawater Greenhouse designed by Charlie Paton is an invention that uses the evaporation of seawater at the front of the building to create a cool and humid growing environment for crops inside. The pilot project (pictured) was built in 1992 in Tenerife. Subsequent project locations include Abu Dhabi, Oman, Australia, and Somaliland.
also works toward minimising water loss through evaporation. Other questions related to water management in architecture are water storage and the handling of storm and waste waters.

The organisms developed to survive in arid conditions all have a strategy to minimize water loss, which often includes non-living matter to create shade, trapping a layer of air next to the organism’s surface to reduce the evaporative gradient, or a combination of the two. Numerous species of cacti, for example, are covered in fine white filaments that trap humid air close to the surface of the living tissue to allow the continuation of exchange of gases necessary for photosynthesis. The white filaments, of course, also reflect the sun and thus help in reducing evaporation. This is an example of a static strategy and morphological adaptation to environmental conditions – these concepts will be explained further in the next chapters on how to apply biomimicry in architectural design.

Another challenge concerning water is in the question of its storage. Water storage in buildings is usually done in the form of rigid tanks with small regard for architecture. However, plants in conditions where rain is scarce but intermittent have evolved to have structures that can absorb large quantities of water in a short period of time by means of expanding their tissue as cacti, or storing their water underground in large roots.212

The Namibian fog-basking beetle (Onymacris unguicularis) is a good example of adaptation to a resource-constrained environment with its ability to harvest water from the desert air (figure 40). The beetle’s shell – which is matt black and in the clear desert night radiates heat to become slightly cooler than the surrounding air – has bumps which are hydrophilic and are surrounded by a hydrophobic surface – this allows the beetle to harvest water effectively from relatively dry air, as the surface is ideal for water droplets to form and stay in spherical shape. This has inspired projects with similar water-harvesting schemes, such as the Seawater Greenhouse (figure 42), the Las Palmas Water Theatre (figure 41) and the Sahara Forest Project.

Some other great strategies for water harvesting are exhibited by a species of laurel (Ocotea foetens) and the thorny devil lizard (Moloch horridus). The tree gathers water through condensation from humid air on its impressive surface area of leaves, while the lizards skin is covered in fine capillary grooves so that water from a damp patch of ground tracks up from its feet and towards its mouth.213 Water in building structures is not usually something to strive for, but with careful design this capillary action could be utilised in water harvesting in buildings.

An important question for an architect or any designer of the built environment is how to manage storm waters in a sustainable way, not just channelling them in pipes away from the site as soon as possible. Here, approaching the building project as part of a closed-loop system is beneficial and biomimetic. Landscape architects have long favoured solutions where the waters are treated on site with rain gardens, constructed wetlands, filtering, absorption, encouraging evaporation, and reserve pools. An interesting project with a systems-thinking approach to water management is the Hammarby Sjöstad residential area (2004–2016) in Stockholm, Sweden. The Hammarby model of energy, waste, and water treatment is a forerunner in the design of an urban area with ecosystems thinking and water management (figure 43).
The Hammarby model

Energy
1. Combustible waste is used to generate district heating and electricity.
2. Biofuels are used to generate district heating and electricity.
3. District heating and cooling are both produced using the purified wastewater.
4. Solar energy is converted into electrical power or used to heat water. Electricity should bear the Good Environmental Choice label, or equivalent.
5. Biogas is extracted from sewage sludge and food waste.

Waste
6. Combustible waste is converted into district heating and electricity.
7. Food waste is biodegraded to produce biogas that fuels vehicles, whilst the mulch becomes nutrient-rich fertiliser.
8. All material that can be recycled is sent for recycling: newspapers, cardboard, glass, metal, etc.
9. Hazardous waste and electrical waste is recycled or sent to landfill.

Water & Sewage
10. Rainwater from the streets is treated locally and hence does not burden the wastewater treatment plant.
11. Rainwater from courtyards and roofs is led off into Hammarby Sjö.
12. Wastewater is treated and then helps in the production of district heating and cooling.
13. Biogas is extracted from biodegraded sewage sludge.
14. The biodegraded sewage sludge is used as fertiliser.

Fig. 43
Above: The Hammarby model of energy, waste and water treatment, a forerunner in the design of an urban area with ecosystems thinking and water management.

Fig. 44
On the right: The Hammarby Sjöstad stormwater canal.
The Hammarby water treatment system includes:
- Prepared soil for filtration of storm water from streets.
- A storm water basin with wetland for storm water from streets.
- A storm water basin for filtration.
- A channel for storm water from buildings and gardens only (figure 44).
- Green roofs and yards to collect storm water locally.
- An experimental wastewater treatment plant.
- A pumpstation for wastewater.

Wastewater treatment is an important part of the water cycle of built projects. Just in the last half-century we have lost significant quantities from the world’s soil in the linear flow of nutrients from the earth through food and people’s digestive systems into traditional waste water treatment plants. Following on the idea that any ‘waste’ is a resource yet to be utilised, there is a potential here for integrated wastewater treatment strategies in built projects. In Hammarby Sjöstad, biogas is extracted from biodegraded sewage sludge and the sludge is then further used as fertiliser. Another example of a more local sewage treatment system is the Living Machine®. The idea of using versions of wetland ecosystems to treat wastewater was conceived by biologist Dr. Käthe Seidel in the 1950’s at the Max Planck Institute. The Living Machine® uses an ecosystem of plants and microorganisms cultivated in wetlands to sewage or industrial waste to such a level that it can be used locally for toilet flushing or irrigation. The architect or planner’s role is to enable and advocate system loops like this as early on in the planning process as possible.

Homeostasis is the tendency of a system, especially the physiological system of higher animals, to maintain internal stability by means of the coordinated response of its parts to any situation that would disturb its normal condition or function. This is something architecture traditionally strives for as well – maintaining a set comfort level within a space. One of the most important components of homeostasis in buildings is thermoregulation. This presents vastly different challenges depending on the location of the building project and whether the need is for cooling or staying warm. However, if the design of a building is done from the viewpoint of light of heat regulation, by either the orientation of the design or through enclosure systems that can mitigate temperature variances, less energy needs to be used to mechanically or electrically balance the interior conditions. This means a shift from in energy use from active to passive systems, and a challenge for architects to design buildings that naturally function with their immediate site. Passive systems in this context might include both static adaptive strategies and dynamic adaptive mechanisms, if they function without external energy input or mechanical actuators.

Strategies for stabilising temperatures are important in regions where temperatures fluctuate between day and night, as well as strategies for regions where the challenges between seasons differ greatly. In Finland, for example, the winter is cold and the little sunlight that is available comes from a low angle, whereas in the summer, solar radiation is available almost 24 hours a day and from a higher angle than in the winter. In this scale of swings in conditions different approaches to adaptive strategies are called for. Not all possible strategies for keeping warm, keeping cool, and for stabilising temperatures will be listed here, but rather some examples that might provide inspiration for the architect.
The main sources of heat for organisms are based on solar energy: either directly through radiation or indirectly by metabolising food (that has grown with solar energy). The reaction of an organism to the gained thermal energy depends on its living conditions: in cold climates the main concern is to minimize heat loss e.g. with insulating layers such as fat or fur; in hot climates strategies of cooling and of avoiding solar heat gains altogether are essential. The way in which architects could gain insights for innovative thermal control is to look at these different adaptive strategies. Heat is transferred in four ways: radiation, evaporation, conduction and convection. Cooling strategies responding to these different ways vary, but the number one is to avoid heat altogether – in architecture this means most obviously avoiding solar heat gains by incorporating shading. A building’s orientation on the site, self-shading by the shape of the building, and additional shading systems are all basic and static strategies to the avoidance of sun. A dynamic strategy would be a shading system that responds directly to the presence of solar radiation with either heat or light as its stimulus. The next part of this work will give some examples of these kinds of strategies.
Pawlyn suggests that perhaps one the most elegant solutions to trapping solar energy has developed in the nest of the Eastern tent caterpillars (*Malacosoma americanum*) (figure 45). Their communal nests are built from multiple layers of silk and face southeast to benefit from the warming of the morning sun. The combination of the orientation of the nest and its insulation keeps the inner temperature of the nest at least 4°C above the ambient temperature. Reindeer, on the other hand, have a dense under layer of fur that traps warm heat next to their skin, while the longer and coarser hairs act as a ‘raincoat’. These are static strategies for maintaining homeostasis, but the penguin has a more dynamic strategy. In water, their plumage is pressed close to their body to ensure streamlined swimming, but on land they lift their feathers to maximize insulation by trapping air in the filaments of their feathers. In addition to this dynamic strategy they also employ the static strategy of a layer of subcutaneous insulating fat. The lesson to take from the penguin is to perhaps incorporate more dynamic systems of regulating heat in buildings than a static layer of insulation. Intelligent systems in buildings can regulate the internal conditions admirably, but this could also be done with systems that respond directly to changes in the environment without external actuators, as mentioned in the chapter about materials.

Evaporation of water is an effective means of cooling because water’s heat capacity is high enough for the dissipation of large amounts of heat with a small amount of water. In plants, the *stomata* or microscopic pores on the leaves control the rate of evaporation and the exchange of gases involved in photosynthesis. In higher temperatures the stomata open wider to allow for more water to evaporate and cool down the tissue. In an extreme situation the leaves lose so much water through evaporation that the leaves wilt, which subsequently reduces the surface area of the leaf and the amount of solar radiation it receives. The World Water Headquarters competition proposal by Exploration Architecture and Charlie Paton proposed two kinds of cooling: through the evaporation of seawater and radiative cooling into the air (figure 46). Radiative cooling was briefly mentioned in the previous chapter as a part of the water harvesting strategy of the fog basking beetle.

A now already classic example of biomimetic inspiration for cooling is the case of the Eastgate Centre in Harare, Zimbabwe, by architect Mick Pearce and Arup (1996). The office building and shopping complex achieves quite steady conditions without conventional air conditioning or heating. While outside temperatures typically range from 5°C to 33°C, the interior is maintained at 21°C to 25°C. Pearce studied the termite mounds of *M.Michaelseni* and *M.Subhyalinus* as his primary source for inspiration (figure 47). The termite mounds appeared to use a combination of steady ground temperatures and wind-induced natural ventilation to take care of their thermoregulation. To mimic this, the building is a heavy masonry construction, with added external shading to minimise solar gains. The night air in Harare, to which the termites are also adapted, drops in temperature during the night, and this cool air is drawn into a plenum between the first and second floors of the building. The cool air is then circulated into a concrete labyrinth with maximum surface area for maximised heat transfer. During the day, air from these cool voids is drawn into the occupied spaces. Warmer air is drawn out through 48 masonry chimneys with the help of wind velocity at the top of the chimneys, the buoyancy of the warmer air, and a back up of low-speed fans. Some recent research into termite mounds by Rupert Soar and J. Scott Turner has, however, questioned whether the strategies of thermal stabilisation in a termite mound are as straightforward as had been previously believed. It seems that the inner temperature of the mound is not that
Fig. 47
All images on the page:
The Eastgate Centre and its cooling system inspired by termites’ nests.
stable, and the main stabiliser is the thermal mass of the ground beneath rather than ventilation or evaporation. The way in which termite mounds use wind seems to be more complex that previously believed and works more like lungs with rhythmic ebb and flow rather than a unidirectional flow of air. This does not, however, take away from the success of the original analogy of the cooling in termite mounds and the successful cooling strategy in the Eastgate Centre. Even though the underlying science might have been superficially understood, the biomimetic solution works in the situation it was intended for.

As of the writing of this work, engineer Salmaan Craig is conducting research at the Harvard Center for Green Buildings and Cities on how to design thermally autonomous buildings by using, according to his own terms, ‘smart geometry’ and ‘dumb materials’. His work includes research into porous walls that could ‘breath’ and make the use of special air vents and ducts redundant. Previously he has devised a solution for a roof that is insulated against the sun but allows for the radiation of infrared heat at night. This involves a layer of insulation on top of a concrete roof that blocks most of the sunlight while it funnels long-wave radiation with reflectors towards transparent apertures. Test panels of this passive solution have shown that it would be possible for the room temperature to drop 13°C below ambient.

A biomimicry approach can be also beneficial in the scale on urban design in the mitigation of the heat island effect. Cities exhibit their own microclimate and are typically warmer than the surrounding rural areas – this is called the urban heat island (UHI) effect. The effect is largely the result of the modification of surface properties leading to greater absorption of solar radiation, reduced convective cooling and lower water evaporation rates. The urban heat island effect can be mitigated by introducing ‘greenspace’, such as urban forests, parks, street trees and verges, private gardens, fringes of transport corridors and vegetated roofs and façades. Vegetation affects the thermal balance in cities bot directly and indirectly. Directly, it influences the microclimate by reducing surface and local air temperatures, which affects air temperatures in larger areas. In an indirect way, it reduces heat transfer into occupied spaces and thus reduces mechanical cooling loads and any heat emissions caused by humans back into the urban climate. Basically the use of vegetation to lower temperatures in urban areas is a form of direct bioutilisation. However, it can be argued to be in essence biomimicry, as the basic principle behind it suggests that the urban area is seen as part of an ecosystem, and the strategy applied results in greater resiliency and sustainability through the reduced need for mechanical thermoregulation.
Managing the consumption of energy is key in the production of building materials, in the building process itself, and in the maintenance of the building during its occupation. All of the categories presented in the previous chapters about where to use biomimicry have, from a purely utilitarian point of view, the same underlying goal: to reduce the consumption of energy. Of course, the architect also has other aspirations in mind, and reducing a design task to the bare necessities of physics should not be the aim. The challenge for architects is what the pursuit of minimizing energy use and perhaps maximising energy production means in the context of architecture.

In his work, Pawlyn has included into the question of energy management the question of ‘How should we produce energy for our buildings?’ This approach would imply the use of integrated solar technology in architecture, or the use of solar energy from indirect sources: wind energy or wave energy. Some examples in the case studies to be presented in the next part of this thesis have integrated solar technology in their architecture in contrasting ways. The Freiburg Heliotrope and the Adaptive Solar Façade both have the goal of energy production as a key element in their design. The main focus of energy management in architecture, however, should not be in the direct use or production of energy by a building. Biomimicry in terms of energy management could go much further that the systems directly linked to the building itself. The systems boundaries of a building project should be widened to take into consideration the energy management of the production of materials, the building process itself, the maintenance and ultimately the disassembly of the building and the management of subsequent building waste. This is an example of the way biomimicry could help address indirect and systemic challenges in energy management and ties in with the ecological analogy inherent in biomimicry (see chapter 4.3, The ecological analogy).
The most important question to the practising architect is how to actually use biomimicry in their work. As with any design practice, knowledge is gained with experience. However, to anyone not experienced in the approach, simply being aware of the phases to be expected in the process can be helpful. In addition to learning from our own experience, learning from other designers’ experience gives us a chance to avoid some of the most common pitfalls described in chapter 8, such as the insufficient abstraction of the emulated principles or non-collaboration with life sciences. In this chapter we will briefly go through some proposed design processes from the engineering perspective as well as the life sciences perspective, and then formulate our own approach in the next chapter.

Knippers and Speck have outlined the stages of biomimetic design based on their work on e.g. the Flectofin shading system inspired by the *Streglitzia regina* flower. They have identified two different kinds of design processes: a ‘bottom up’ process pushed further by the push of biological research, and a ‘top down’ process pulled on by the need to solve a technological problem (figure 48). They point out, however, that the linear understanding of biomimetics illustrated here is sufficient only if the focus is on simple functions or technical problems. In architectural terms, a different set of requirements have to be taken into consideration on the level of functionality and aesthetics, and this has to be done within the boundary conditions of the architectural design task. This will be apparent in chapter 12, *Case One*, where the process of development from the biomimetic proto-architectural Flectofin shading system to a functioning façade with a strong architectural language will be described.

As with the question of what is successful biomimicry, Knippers and Speck have here provided the biomimetic engineering perspective, and Benyus and Baumeister through Biomimicry 3.8, the more holistic and ecological biomimicry perspective. In contrast to the linear process described by Knippers and Speck, Benyus and Baumeister have outlined the biomimicry design process in a non-linear way. Their *Biomimicry Design Lens* offers, as do Knippers and Speck, two routes to the design, but through a cyclical process: ‘challenge to biology’ pulled by a specific problem to be solved, and the other, ‘biology to design’ pushed by a biological insight to be manifested in a design. Pohl and Nachtigall give a further definition of how biomimetic innovation might occur: either nature actually provides the driving stimulus for the certain development (the ‘bottom up’, biology push of Knippers and Speck), or the development of technology occurs without knowledge of biological precedents of such structures (figures 49 and 50). In this case, a functional similarity of a function is established *a posteriori*, which has been the case in many instances that have been dubbed biomimetic without the architect’s initial aspiration for such analogies.

None of the aforementioned ways of outlining a design process are strictly specific to architecture. The ones developed by Knippers and Speck are too linear to cover the complex and interconnected process of an architectural design task, and the ones presented by Biomimicry 3.8 are perhaps too general, as they are meant to be applicable in any design task or innovation process. An improved model for the biomimicry design process will be introduced in the next chapter, with the aim of combining the engineering-oriented and the life sciences approaches.
Fig. 48
On the right: The linear abstraction process according to Knippers and Speck.

Fig. 49
Below left: The Biomimicry Design Lens, Biology to design.

Fig. 50
Below right: The Biomimicry Design Lens, Challenge to biology.

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‘Top down’

6 BIONIC PRODUCT
5 TECHNICAL IMPLEMENTATION
4 ABSTRACTION, DETACHMENT FROM BIOLOGICAL MODEL
3 UNDERSTANDING THE PRINCIPLES
2 BIOMECHANICS, FUNCTIONAL MORPHOLOGY, AND ANATOMY
1 BIOLOGICAL RESEARCH

‘Bottom up’

1 TECHNICAL PROBLEM
2 SEARCH FOR BIOLOGICAL ANALOGIES
3 IDENTIFICATION OF APPROPRIATE PRINCIPLES
4 ABSTRACTION, DETACHMENT FROM BIOLOGICAL MODEL
5 TEST TECHNICAL FEASIBILITY AND PROTOTYPING
6 BIONIC PRODUCT
The Biomimicry Design Cycle is based on a synthesis of the processes outlined in the previous chapter and the author’s own experience with utilising biomimicry in architectural design. The Biomimicry Design Cycle emphasises the cyclical nature of the whole process as well as the reciprocal nature of the different phases in relation to each other. The phases of the Design Cycle will be illustrated through an exemplary line of inquiry – developing adaptive architectural envelopes with the adaptive strategies of plants as inspiration. It is essential to illustrate the process through a specific pairing of natural inspiration and architectural endeavour to get a better understanding of the subject than with broad generalisations – as we have come to see, broad generalisations do not get us far in biomimicry. In the case studies in the next part of this thesis, this line of inquiry will be shown to its final phase by illustrative case studies of façade solutions inspired by the adaptive solutions of plants.

The Biomimicry Design Cycle includes eight phases in cyclical and reciprocal relation to one another:

- Technical problem.
- Search for biological analogies.
- Identification of appropriate principles.
- Abstraction, detachment from biological model.
- Introducing system feedback loops (architectural expression).
- Testing technical feasibility and prototyping.
- Biomimetic proto-architectural product and architectural expression.
- Evaluating architectural expression against biomimetic performance.

In this model, the process of biomimetic research is ‘top-down’, but the architectural design process is ‘bottom-up’. The process of biomimetic research is pulled by the architectural ambitions of the designer, but until the abstraction of the desired performative quality from the biological model is made, the possible directions of the architectural design are pushed by the qualities of the biomimetic role model. When a level of sufficient abstraction is achieved, the interaction is reciprocal: the abstraction of the biomimetic role model leads to certain boundary conditions within which the architectural expression is established.

The cyclical nature of the process is outlined in the proposed process diagram (figure 51). The starting point of the process can be either the drive for a certain kind of architectural expression, a specific technical problem or, realistically, a combination of the two. As expressed before, these aspects are interrelational, but the architectural expression would benefit especially from innovations relating to light, enclosure and patterns, as the more technical and ‘engineerable’ problems relate to structures, materials, zero-waste systems, thermoregulation, and water and energy management. In this interconnected and cyclical process, the technical problem arises from the architectural ambition, which in turn is informed by the solutions available to the technical problem. It is helpful here to make clear what is meant by ‘architectural expression’ and what by ‘technical problem’. In simple terms, the former refers to the qualitative and non-quantifiable what and why of the spatial qualities of the design task, whereas the latter refers to the quantitative questions of how the physical realisation of the design works. This process has a technology pull and an architectural push. The different phases of this cycle will be further explained in the following chapters.
Fig. 51
The Biomimicry Design Cycle proposed in this thesis.
The Biomimicry Design Cycle can be entered either through the ambition for a certain kind of architectural expression, or through the search for a solution to a technical problem. The technical problem is taken as the entering point here because in the scope of this thesis, there is no actual site-specific design task to inform the context and boundaries for the architecture. Thus, to illustrate the process, the technical problem will be discussed first. The starting point in the design process is to identify a problem to be solved, a performative function to be achieved with a biomimetic solution. To illustrate the design cycle, the task of designing an adaptive and light-regulating building envelope is taken as a starting point. The choice to cast light regulation in the role of the technical problem can made for a multitude of reasons: the designer's own interest and curiosity towards light-responsive systems; the chance to produce architectural value and spatial variation with different lighting conditions; or to contribute to the comfort of the occupants and the energy balance of the building systems by minimizing heat gains and glare while maximizing views and natural lighting whenever possible.

The problem of adaptive light regulation leads to architecture that can react to environmental influences in a positive way. To gain a positive and not a deteriorating effect, the adaptive reactions need to be integrated carefully in the design. Petra Gruber has listed different ways reactions on a building scale can occur:

- Opening/closure – control of access of living organisms, material or energy. In this case opening and closing of building/architectural elements can be applied to control the access of solar energy.
- Locomotion and movement of building parts. More dynamic solutions to the control of solar gains could be e.g. solar tracking façade elements.
- Change of properties of elements. This could mean for example changes in the permeability of materials depending on ambient conditions.
- Change of properties of space.
- Change of internal environment.

Once the technical problem has been identified, the search for biological analogies can begin. In an architectural context, the problem does not necessarily need to be specific in the beginning of the process, as a certain ambiguity gives room for different possible analogies in the next phase of the process. In this instance the problem can be identified as opening and closure of architectural elements to control light and thermal conditions. How exactly this opening/closure might manifest itself will be explored through the search for biological analogies.

The search for site-specific adaptive solutions to light conditions leads easily to the world of plants, as they need sunlight to survive, and yet, as buildings, cannot relocate in response to changing environmental conditions, and so must rely on different adaptive strategies to maintain homeostasis. Adaptation solutions in plants can be roughly described within three categories:

1. **Morphological or structural**: relating to an organism’s shape, size, pattern or structure.
2. **Physiological or functional**: relating to an organism’s chemical processes.
3. **Behavioural**: relating to how an organism acts.

Furthermore, the way that plants have adapted to challenges from their environments can be described as either *dynamic mechanisms* or *static strategies*. These
López et al. have devised a design concept generation process based on a proposed data collection and classification system of plants’ adaptive strategies to help in the design of plant-inspired dynamic façades (figure 52). After a data collection has been organised of plants and how they interact with their environment, a biomimetic design methodology can be suggested which then leads to concept designs for adaptive architectural envelopes. According to this process, there are four stages in the design process from nature to engineering: analysis, synthesis, evaluation, and implementation. The accompanying diagram is intended to aid in the first three phases of the process. The stages of this proposed process are roughly equivalent to the contents of phases 2 to 4, and 6 in the Biomimicry Design Cycle:

- **Analysis / Search for biological analogies and identification of appropriate principles.**
  This phase includes the first the analysis of the technical problem at hand in order to understand what are the desired qualities or mechanisms to be searched for in the data collection of biological examples.

- **Synthesis / Abstraction, detachment from biological model.** A critical phase is the appropriate understanding and synthesis of the principles found in the biological examples, and a sufficient level of abstraction of those principles before trying to implement them into a design.

- **Evaluation and implementation / Testing technical feasibility and prototyping.** Once the functional principles have been abstracted, their applicability to the design problem needs to be evaluated, and the technical implementation needs to be tested by prototyping.

The data collection proposed by López et al. to provide architects with a collection of applicable natural analogies is not yet a reality, but some resources with a similar aim are available. Firstly, collaboration with biologists and other life science specialists is the most important resource. If this is not possible or desirable in

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**Fig. 52**

Design concept generation proposed by López et al. based on a proposed Data Collection and classification system.
the first stages of the design process, one can start with some resources online: asknature.org, maintained by the Biomimicry Institute, provides a database of biomimicry solutions and possible natural inspirations organised by types of adaptive strategies.

To find a solution to the problem identified in the previous chapter – the opening and closure of architectural elements to control light and thermal conditions – the designer needs to look for plants that have an adaptive strategy including behavioural mechanisms. Some structural mechanisms might be useful as well, if they rely on self-actuating properties of the organic material, and if these properties can be abstracted and interpreted in a building material. The next chapter focuses on the possibly architecturally viable principles found in biological models.

Movements of plants are stimulated both by internal signals and by signals from the environment. The capability to sense and react to external stimuli at different timescales is essential to the adaptive strategies of plants: many physiological aspects, like self-protection, intake of nutrients and reproduction can rely on this capability. Some plants have even evolved the ability to react to mechanical stimuli in seconds, despite lacking nerves and muscles.237

Nastic movements are specific to the species and predetermined by the location and structure of the driving motor or its parts (figure 53). Tropic movements take place in directions determined by some vectorial environmental signal, for example gravity or light. Hyponasty occurs when the growth of cells is faster in the bottom side of a plant organ, and epinasty occurs when the growth is faster in the top part. In practice, this is the principle behind convex or concave leaves. A leaf in a flower bud starts out with hyponastic growth, making the leaf cling tightly and closely to the bud, but as the flower matures, the leaf transitions into epinastic growth, causing the shape of the leaf to transform from concave to convex, and thus opening the flower.238

All plant movements in general, whether in growing or mature tissue, are based on physical force exerted against the structure of the cell walls. The location of the motor tissues, the mechanisms by which they work, and the signals that control the mechanisms are what creates diversity in plant movements.239 The types of movements can be categorised into autonomous and non-autonomous movements. Active autonomous movements are characterised by motor organs driven by a change of turgor pressure, i.e. the internal pressure of the cells. The motor organs where the pressure changes occur are called pulvini (pulvinus, singular). Passive autonomous movements occur as a direct result of changing physical circumstances, for example the bending of a spruce cone scale due to desiccation. Non-autonomous movements refer to mostly reversible deformations that occur when an external trigger or the direct application of mechanical forces causes the release of stored elastic energy.240 Some motors, like that of the spruce cone scale, employ anisotropic changes in their cell dimensions to execute drastic changes in the architecture and spatial organisation of the plant or pant organ.241

Some on these principles will be examined further through their abstraction and implementation in various case studies in the next part of this thesis: non-autonomous movements as the inspiration for the Flectofin shading system and the façade of the Yeosu Pavilion; passive autonomous (nastic) movements as the inspiration for the
HygroSkin Pavilion, DoSu’s ‘breathing metal’ designs, and to some extent the Homeostatic Façade System; and active autonomous tropic movements as the inspiration for both the Adaptive Solar Façade and the Freiburg Heliotrope.

The necessary level of abstraction depends on the chosen analogy and inspirational mechanism. At the basic level, it is necessary to understand the type of strategy that is emulated, and then proceed to envision how that strategy could be used in a pro-totypical architectural design. It is not desirable to try and emulate the actual mechanisms of the strategies themselves – one should not try and replicate nastic movements in a building component with a direct copying of the turgor pressure mechanism. In this chapter, some proposals on how the principles of the aforementioned plant movements could be abstracted and reimagined with building technology in mind.

According to the design process proposed by López et al., the phase of abstraction can be resolved with three important concepts: application ideas, innovation, and design concept generation. In this case application ideas refers to the ways the adaptive behaviour of plants could be used in adaptive architectural envelopes: either based on a movement through dynamic mechanisms, or material properties through static strategies. Innovation means that challenges taken from the adaptive strategies of plants can enhance innovation both in the engineering and the design sense. Finally, design concept generation involves the observation of biological models and the abstraction of biological terms to constructive terms. The resulting design concept should not be a direct translation of a particular plant, but it should be informed by the study of its function, morphology and nature.

Non-autonomous movements present potential for the implementation of interesting buckling principles, as in the Flectofin shading system, where the bird-of-paradise flower was the inspiration. In the instance of Flectofin, however, Knippers and

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**Fig. 53**

Schematic representation of leaf nastic behaviours (epinasty and hyponasty).
Speck have pointed out that the abstraction of simple functions can be done with a linear understanding of the biomimetic process, but in more complex architectural tasks the abstraction has to be taken further. The Flectofin as well as the subsequent further abstraction and implementation of the principles will be presented in the case studies in chapter 12.

Passive autonomous movements might inspire the use of materials that either through their natural or engineered properties are able to react to changing environmental conditions without external actuators. The principle of nastic motion can interpreted to a level of abstraction where it inspires movement that is based on active and passive components of an element. The active component works in a similar same way as the active side of a leaf: by expansion it exerts force against the passive element, and together the system results in an overall movement, e.g. curving of the element. The abstracted principle could be the implemented for example with the use of thermo-bimetal panels, where one side has a higher coefficient of expansion than the other one, thus presenting a, ‘active’ and a ‘passive’ side. The expansion in the active element in a system inspired by nastic movements could also be realised with a pneumatic structure. One possibility could also be the use of photomechanical materials engineered to react to chosen change triggers in light conditions. Reactions of photomechanical materials can result for example in the expansion, bending and coiling, or twisting of the material.

Active autonomous movements could be abstracted in reference to the stimulus they are a reaction to. In this case, the inspiration is not the mechanism of the movement but the strategy of movement itself, like heliotropism. Heliotropism means motion in relation to tracking the sun, and can present itself either as diheliotropism (tracking the sun) or paraheliotropism (avoiding the sun). Other tropisms include e.g. phototropism in relation to the presence of colour of light, and thermotropism in relation to temperature. When abstracting principles from these movements it is important to keep in mind whether it is the strategy of movement (i.e. tropism) or the mechanism of the movement (i.e. function of the pulvinus) that is being emulated. Both the Adaptive Solar Façade and the Freiburg Heliotrope will show an approach where the strategy of tropism has been applied, but without an analogy to the mechanisms of movement plants use to actuate tropism.

Once the principles extracted from the biological model have been abstracted to a sufficient level, they can be implemented in a physical model. Different materials can be tested for their properties, and the overall principle should be tested in the chosen scale. The technical feasibility of the solution can first be tested as a proof-of-concept model, without emphasis on architectural sensibilities. However, a proto-architectural product cannot be developed without a guiding concept for the architectural use of the solution.

If the technical feasibility of the chosen strategy or mechanism seems technologically or economically unviable, there might be a need to revert back to the previous phase of the process: the abstraction of models from nature. Some insight can also be gained from a parallel focus on the next phase of introducing system feedback loops, as a systems-thinking approach can help in the technical application of the chosen principle.
This phase of the process is not always necessary, but always recommendable. The fundamental ideology behind biomimicry encourages thinking of the project as a closed system, and evaluating its place in the larger network of interconnected systems. As mentioned earlier with regard to zero-waste systems in chapter 9.3, this might mean that the system boundaries of a building and its building process need to be widened to include material production processes, the handling of maintenance and possible future disassembly, but also the societal context and implications of the project.

In simple terms, a system feedback loop creates conditions for a mechanism that can sustain certain behaviour over time. Adjusting the definition of a feedback loop given by Donella Meadows in her book *Thinking in Systems: A Primer* (2008) to be applicable in an architectural project: A feedback loop is a closed chain of causal connections in a system, through a set of decisions or rules or physical laws or actions that are dependent on the behaviour of the system, and back again through a change in the conditions of the system (figure 54). In an architectural context a reinforcing system feedback loop could be the following: changes in the ambient temperature next to the façade system actuate a change in the behaviour of the façade; and also, the changes in the behaviour of the façade have an effect on the temperature of the façade and its immediate environment; this again affects the ambient temperature next to the façade and so on and so forth.

The reason behind introducing system feedback loops is to search for more integrated performance capabilities based on the chosen direction of the design. Nature works in interconnected systems, where one part or function cannot be isolated from another, and this principle should be used to the advantage of the building as a system, and in our chosen example process, to the advantage of the building envelope. The process of introducing system feedback loops is a bit like the process of abstracting functional principles from examples in nature, but in reverse. In the abstraction process, the desirable principles have to be identified and isolated from the desired characteristics from which inspiration is being taken while the interconnectedness of the original system has to be carefully considered. Introducing system feedback loops means adding back to the complexity of the functions of the proto-architectural product. This does not mean that the implementation itself has to be complex, but that whenever possible, additional functions or benefits could be derived from the system.

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*Fig. 54*  
Introducing system feedback loops: If A causes B, can B also cause A?
Once the technical feasibility of the chosen principle has been tested, the result is a biomimetic proto-architectural product. This phase does not have clear boundaries, and the proto-architectural product is not ‘ready’ as long new input can be gained from other phases of the Biomimicry Design Cycle. The biomimetic proto-architectural product, for example a façade element, is being developed constantly in the context of research input from the prototyping phase, the functional repercussions of introducing system feedback loops, and the design input from the architectural point of view. The cyclical nature of this process is illustrated in the accompanying diagram (figure 55).

The architectural expression is informed by the previous phases, and in turn informs the proto-architectural product. Each iteration of the design of the proto-architectural product impacts its biomimetic functionality. Research on the biomimetic model and desired functionality of the product determine the boundary conditions of its architectural design.

The artistic, compositional and functional aspects of the overall architectural design should be taken into consideration as an essential part of the biomimicry design process to elevate it higher than a functional engineering task. Can better biomimetic performance be facilitated by changes to the architecture? Should biomimetic performance be impaired if dictated by architectural needs? The architectural and spatial expression of the design should be evaluated against the desired biomimetic performance – it is then the architect’s task to value these aspects against each other, if there is a conflict. In this thesis it is argued that the innovations achieved by a biomimicry approach should work to the advantage of the architectural expression.

In casual discussion, the word biomimicry often evokes images of biomorphic shapes or something vaguely ‘green’. Biomorphism or ‘green’ architecture, however, is not the always the result of a biomimicry approach, nor should a biomimetic design process lead to such architecture. Biomimicry does not need to be visually evident in a building’s architecture, but rather in the architect’s process and intent. Nevertheless, to promote the virtues of biomimicry, it can be advantageous to express this intent in the architectural expression, even if it does not need to be the most prominent aspect of the architectural language to be used or the most important thing to express.

An important question for the architect to consider is what kind of attitude to exhibit towards the boundary conditions set by the functionality of the biomimetic proto-architectural product or concept. Is the morphology emerging from the biomimetic process something to be celebrated and even exaggerated, or is it to be downplayed and subject to some architectural and stylistic sensibility? Neither one of the options is right or wrong, but simply produce differing architectures. This is evident in DoSu Studio Architecture’s ‘breathing metal’ designs that are further analysed in the case studies. The architectural research installation entitled Bloom (2011) celebrates the morphological language of the thermo-bimetal panels, which curve and open in response to solar heat gains. Another project by the same studio, an on-going research project into a glass panel shutter system based also on the responsiveness of thermo-bimetals, works in the rigid language of rectangular façade panels. It should be noted, however, that the latter project is more in the stage of a proto-architectural project than a complete building design.
López et al. also point out that the biomimetic design concept generation must consider the comfort aspect for human behaviour in addition to their physical needs. Strategies for shading systems, for example, can affect the indoor comfort not only from the viewpoint of thermal comfort, but also by its visual implications.\(^{246}\)

In the next part of this thesis, some illustrative case studies will be presented and analysed in the context of the proposed Biomimicry Design Cycle. The cases have been chosen to present a wide range of strategies and responses to a similar problem. Furthermore, these are all projects that have gone further than a mere concept, and have all passed the threshold of prototyping to an actual built design. This presents the possibility of analysing the projects not just based on their concepts, but more importantly, on how those concepts have been implemented, and how that has affected the architecture in each case.
Designing with biomimicry, references


[168] Ibid., p. 1.


[172] Ibid., pp. 270–271.


[179] Ibid., p. 4.


[181] Ibid.


[187] Ibid., pp. 2–3.

[188] Ibid., p. 3.


[190] Ibid., p. 11.


[192] Ibid., pp. 10–14.


[196] Ibid., p. 15.


[201] Ibid., p. 16.

[202] Ibid., pp. 35–36.

[203] Ibid., p. 36.


[206] Ibid., p. 53.


[208] Ibid., p. 59.


[211] Ibid., p. 65–78.

[212] Ibid., p. 66.

[213] Ibid., p. 67–69.


[220] Ibid., p. 77.

[221] Ibid., p. 78.

[222] Ibid., pp. 80–81.

[223] Ibid., p. 84.

[224] Ibid., p. 86.


[234] Ibid., p. 697.

[235] Ibid., p. 697.

[236] Ibid., p. 698.


[239] Ibid., p. 12.


Case studies
12. Case One

12.1 Identification of analogies

The first case looks at a static strategy manifested as a morphological adaptation. The adaptation that is imitated is the non-autonomous movement in plants caused by the application of external force or the presence of a trigger that causes the release of stored elastic energy. The analogy to nature is present in the morphology and the implementation of materiality as well as in the strategy itself, where the abstraction made is that of a mechanism capable of reversible deformations without injury. In this thesis, however, it is placed in the category of passive strategies because the movement is actuated by the application of an outside force, not an internal actuator like in the case of e.g. materials changing shape because of their inherent properties. An architectural example of a purely static adaptive strategy for shading and solar optimization would be a self-shading mass.

12.2 Flectofin and the Yeosu Thematic Pavilion

Designer: ITKE University of Stuttgart, Soma Architecture and Knippers Helbig Advanced Engineering
Year: 2012
Biomimetic principle: non-autonomous movement in plants, controlled buckling
Inspiration: bird-of-paradise flower

The Flectofin is a hingeless louver system inspired by a deformation principle found in the bird-of-paradise flower (Strelitzia reginae). It is a result of transdisciplinary collaboration of architects, engineers, and biologists at the University of Stuttgart’s Institute of Building Structures and Structural Design (ITKE). The fins in the system are capable of shifting themselves 90 degrees by inducing bending stresses in the spine caused by displacement of a support or a change in temperature of the lamina. The Flectofin and research pertaining to it were the starting point for the design of the façade system in the Thematic Pavilion of the EXPO 2012 in Yeosu, Korea (figure 56). The design of the pavilion was the result of an open design competition won by Soma Architects from Vienna, Austria. The design includes a media façade with 108 individually controllable fins engineered by Knippers Helbig Advanced Engineering (figure 57). The façade can be manoeuvred to adapt to different light conditions and desired effects to allow the staging of lighting effects on the media façade. The façade is 140 metre long in total and varies between 3 and 14 metres in height. An additional challenge taken into consideration in the design of the façade is the high winds speeds on the Korean coast.

Biomimicry approach

The development of a biomimetic innovation from the proto-architectural product of Flectofin into an integrated feature of a building project is a great example of the biomimicry design process. Knippers and Speck, whose take on the biomimetic design process was discussed earlier, have both been part of the team behind the process, and have based much of their insights on it.
Fig. 56
Above: Evening view of the One Ocean, Thematic Pavilion EXPO 2012.

Fig. 57
On the right: One Ocean, Thematic Pavilion EXPO 2012 / soma closeup of the facade louvers.
The starting point of the design process was in this case the need to find solutions to a technical ‘problem’, namely the interest to find innovations in the movement of structures. Jan Knippers had already worked extensively on kinematic structures (e.g. the Bascule Bridge in Kiel Horn, Germany by Schlaich Bergemann and Partner), and was interested in how to reduce the complexity in moving structures. He argues that the question leads almost automatically to the study of natural role models and to those of botany especially, as many plant organs move without mechanical elements. Some ways in which plants do this were explained in the chapter about identifying appropriate principles for abstraction.

The research of the ways in which plant movements could be used technically lead to the development of the elastic kinematics for a façade shading system. According to Knippers and Speck, the process exemplified a ‘top down’ process of biomimetics, pulled on by the need to solve a technological problem. The screening of various plants and their strategies and properties suitable for analogy lead to the non-autonomous movement of the bird-of-paradise flower (Strelitzia reginae). The flower has two petals that are grown together to form a perch for pollinating birds. When a bird sits on this perch to get to the flower’s nectar, its weight causes the petals to bend down, which in turn causes the lateral unfolding of the petals to expose the otherwise protected nectar (figure 58). From an engineering perspective, the principle of the mechanism of the petals, consisting of fibre-reinforced ribs, lamina and wings, could be gradually abstracted to a simpler mechanism consisting of a thin shell element attached to a beam (figure 59). The bending and unfolding mechanism is based on a non-symmetrical bending motion that is triggered by torsional buckling induced by the uniaxial bending of the attached beam. The principle was then tested with physical models and numerical simulations to produce the prototype façade shading system Flectofin (figures 60 and 63). The lamellas of the system consist of fibreglass-reinforced plastic to allow for large elastic deformations by offering low bending stiffness and high tensile strength. The system affords potential for application in curved façades, because there is no straight turning axis, but instead a bent backbone. Furthermore, the lack of mechanical and maintenance-intensive parts as hinges or joints holds promise for reduced maintenance costs compared to a more mechanical shading system.

Initially it was attempted to scale the Flectofin system to the size of the Thematic Pavilion. However, this proved problematic on two different fronts: firstly, the design on the system did not meet the requirements of the architectural expression of the pavilion; and secondly, the system could not withstand the high local wind loads without additional structural reinforcement. The initial biomimetic inspiration from the bird-of-paradise-flower and the resultant proto-architectural product had to be thus taken to another level of abstraction for them to be applicable in the architecture of the pavilion (figure 61). The façade is made of slightly curved plates that are supported by two hinged corners at the top and the bottom (figure 62). The other two corners receive a small compressive force applied in the plane of the fin, which the leads to controlled buckling. The developed system has locally smaller strains than the Flectofin, but does not open its fins completely. The fins of the façade are, as with Flectofin, made of fibreglass-reinforced plastic with a thickness of 9 millimetres, a width of 1.25 metres and heights up to 14 metres. The sides with less elastic deformation have an additional stiffener. In its opened state the system is very rigid against high wind loads due to its curved geometry and residual stress state, whereas in its closed state the adjacent fins are clamped together to withstand high wind without damage.
Fig. 58
The biomimetic model for the movement in Flectofin, the pollination mechanism of the bird-of-paradise flower (Strelitzia reginae).

Fig. 59
Analysis and abstraction of the elastic deformation of Strelitzia reginae.

Fig. 60
Simple physical model as a first-level abstraction of the kinematic system.

Fig. 61
The kinematic principle of the Yeosu facade, further abstracted from the principle of the Flectofin.
This case is an illustrative example of the sometimes contrasting demands of biomimetic performance and architectural expression. The initial design of the Flectofin did not match the architectural language of the Thematic Pavilion, and so a process of re-negotiating the design and functionality of the façade system was needed. The biomimetic proto-architectural product had to be further developed with research input from the prototyping phase, the functional repercussions of introducing the system into a building scale, and the design input from the architectural point of view. The cyclical nature of this process was illustrated in a previous chapter detailing the proto-architectural phase of the Biomimicry Design Cycle. In the process from Flectofin to the façade of the pavilion, Knippers and Speck state that the final design was able to match the initial intentions of the architects and offer a favourable ratio of structural stability and actuation energy. The potential contrast between the needs of architectural expression and biomimetic functionality was resolved in favour of both demands.
Figure 7. Simple physical model as a first-level abstraction of the kinematic system in the Strelitzia flower (adapted from Poppinga et al. 2010b). Courtesy of WIT Press from the book C A Brebbia (ed) 2010 Design and Nature V pp 403–10.

Figure 8. Prototype of the facade shading system based on the Flectofin R⃝ produced in collaboration with the industrial partner Clauss Markisen (adapted from Lienhard et al. 2011b). Function will also increase the durability of the biomimetic facade shading system.

3.1. Biomimetics in the architectural design process—design of the thematic Pavilion EXPO 2012

The opportunity of introducing such systems on a larger scale in an architectural design will be presented at the Thematic Pavilion at EXPO 2012 in Yeosu, Korea (figure 9). A kinematic media facade with 108 individually controllable fins is planned on the pavilion side facing the expo. The design is the result of an open design competition which was won by SOMA architects (Vienna, Austria). The technical concept of the kinematic fins comes from Knippers Helbig Advanced Engineering, Stuttgart, New York. The facade can adapt to light conditions and physical building conditions and allows the artistic staging of special lighting effects. It has a total length of 140 m and a height of between 3 and 14 m, and is designed to withstand the very high wind speeds on the Korean coast.

It was initially attempted to scale Flectofin R⃝ to the size of this facade. However, this proved to be difficult in its original configuration. On the one hand, it did not fulfil all aspects of the architectural design; on the other hand, without additional structural reinforcement, it does not offer enough stability to withstand the high wind loads. Inspired by the research on plant movements, another kinetic system has been developed (figure 10). The facade is made of slightly curved plates which are supported by two hinged corners at the top and the bottom. In the other two corners, a small compressive force is applied in the plane of the fin, which leads to a controlled buckling. This principle shows locally smaller strains than the Flectofin R⃝.
13. Case Two

13.1 Identification of analogies

The second case looks at a dynamic strategy manifested as one of the two major behavioural adaptations in plants, nastic movements. In this case they are passive autonomous movements, as the movement is the direct result of changing physical circumstances. The examples given here both approach the parallel to nastic movement with a similar solution – the application of materials that react to changes in their environment through their innate responsive capacities. The natural analogy is present in both as an ecological analogy drawing from the adaptive strategy as well as perhaps even an anatomical analogy by the implementation of responsive materials to produce architectural elements analogous to those of the moving parts of plants.

13.2 HygroSkin Meteo-sensitive Pavilion

The project is a travelling pavilion that was commissioned by the FRAC Centre Orleans for its permanent collection in 2013 (figure 64). The pavilion has a modular wooden skin that is designed and produced using the self-forming capacity of initially planar, thin plywood sheets to form conical surfaces based on the material’s behaviour relative to ambient humidity. The pavilion has a weather-responsive aperture within each of its robotically fabricated concave surface modules. The responsive skin of the pavilion adjusts its porosity in direct response to changes in ambient relative humidity. The pavilion’s envelope is at the same time a load-bearing structure and a metereosensitive skin, is computationally derived from the elastic bending behaviour of thin plywood sheets. The apertures respond to relative humidity changes within a range from 30% to 90%, which equals the humidity range from bright sunny to rainy weather in a moderate climate. The pavilion constantly adjusts its degree of openness and porosity in direct feedback with the local microclimate as it modulates the light transmission and visual permeability of the envelope.

The architect was inspired by the moisture-driven movement that can be observed in spruce cones. When the cones are fresh and still in the tree, the scales of the cone are pressed tightly along its surface to protect the seeds inside. However, when the cone falls from the tree and starts to dry up, the change in the scales’ moisture content makes them open up and release the seeds (figure 66). This is an example of an adaptive strategy that manifests itself as a behavioural adaptation. In this case the behaviour is actuated by the inherent capacity of the material, and requires no input of energy, sensory systems or motor functions. The responsive capacity of the material is a result of its anisotropic hygroscopic characteristics. Hygroscopicity refers to a material’s capability of taking in moisture from the atmosphere when dry and yielding it back when wet; anisotropy on the other hand means that the materials characteristics are directionally dependent.
Fig. 64
Above: The Hygraskin Meteorosensitive Pavilion as exhibited in the ArchiLab 2013 exhibition at the FRAC Centre, Orleans.

Fig. 65
On the right: The Responsive Surface Structure II (2008), by Achim Menges and Steffen Reichert.
The project is based on over six years of design research investigating the biomimetic principles offered by the spruce cone in the designing of climate responsive architectural systems that would function without sensors, motors, or even operational energy input (figures 65 and 67).\textsuperscript{257} The behaviour of the scales in a spruce cone is enabled by the bilayered structure of the scales’ material: the outer layer of the scales reacts to the increase or decrease in humidity by expanding or contracting, while the inner layer remains relatively stable. This causes a change in the scales’ shape and makes it either open or close. The behaviour is similar to nastic movements in plants caused by the change in turgor pressure of cells. This behaviour can be also abstracted and emulated with the use bimetal, as will be shown in the next case study example.

The anisotropic behaviour of wood was used in the development of a humidity-responsive veneer-composite element based on quarter-cut maple veneer. Wood responds to the changes in ambient humidity with a change in the distance between the microfibrils in the wood tissue, and this results in anisotropic change in dimension. This dimensional change can be used to actuate shape change in a responsive proto-architectural element. According to Menges, the developed material can be physically programmed to compute different shapes in response to changes in relative humidity. There is no need for external energy input or actuators, as ‘the material structure itself is the machine’.\textsuperscript{258}

The overall architectural expression is the result of the biomimicry process that has lead to the design. The process seems to have followed a ‘biology push’ pattern, where the innovation of a self-actuating material has resulted in the design of architecture that could best showcase the innovation and its potentials. Achim Menges’ prior research in spruce cone inspired solutions to responsive architectural systems have in this case filled the six phases of the Biomimicry Design Cycle leading up to a biomimetic proto-architectural product and its implementation in the architectural expression of the pavilion: identifying the technical problem, searching for biological analogies, identifying appropriate principles, abstraction, systems thinking, and testing technical feasibility and prototyping.

The most striking aspects of the architectural expression are the constant fluctuations of enclosure, permeability and illumination of the space. This serves as proof that biomimicry has in this instance been used first and foremost to serve the architecture itself. The approach has left room for the designer to hone the language and expression they have used in the implementation of the biomimetic innovation. Biomimicry has been a tool in the design process, not the sole defining element.
Fig. 66
On the right: Abstraction and transfer of the biological principle of shape change induced by hygroscopic and anisotropic dimensional change.

Fig. 67
Above: Meteorosensitive Morphology installation (2012) at Centre Pompidou is another collaboration between Achim Menges and Steffen Reichert.
13.3 Bloom, ‘metal that breathes’

Designer: DoSu Studio Architecture, Doris Kim Sung
Year: 2011
Biomimetic principle: passive movement inherent to the material
Inspiration: human skin

The principal designer of the Bloom installation, architect Doris Kim Sung of DoSu Studio Architecture, describes the project as a ‘sun-tracking instrument indexing time and temperature’. The installation was originally displayed at the Materials and Application Gallery in Los Angeles from November 2011 through to August 2012 (figure 68). The pavilion’s responsive surface is made primarily out of 14,000 smart thermo-bimetal tiles, and no two pieces of the installation are alike (figures 69 and 73). Each piece serves as its own actuator and curls a specified amount when the outdoor ambient temperature rises above 21°C, or when the sun penetrates the surface. The intention of the canopy-like pavilion is to function in two different ways: first, to act as a sun-shading device that regulates the amount of solar gains passing through the skin when the sun hits it; and second, to work as a ventilating system in other areas so that hot air trapped under the canopy can move through and out when necessary (figure 72). The function of each of the 14,000 tiles has been calibrated specifically to their location, the angle of the sun and the curling of the element.259

Architect Doris Kim Sung was a biology student before her architecture career, and has a bioinspired or biomimetic approach in many of her designs. The inspiration for her work with thermo-bimetals was the human skin’s ability to naturally regulate the temperature of the body.261 One might ask then, why is this project presented as an example of using the adaptive strategies of plants in biomimicry design? The reason is that even though the initial inspiration of the design was the function of the human skin, the mechanical implementation of the function is analogous to the passive autonomous movements in plants. The cooling function of the skin works with a different mechanism than the Bloom. It should be noted, however, that this interpretation of the analogy has been made by the author, and not the architect herself.

The starting point for Kim Sung’s work has been the view that building skins should be more like human skins in the way they maintain homeostasis. They could and should be much more dynamic, responsive, and differentiated depending on the location of the parts of the skin. Her research towards these ambitions has turned to smart materials, especially thermo-bimetals (figure 70). Thermo-bimetals are laminations of two different metals with two different coefficients of expansion. When heated, one side of the laminate will expand faster than the other, and this will result in a curling action. According to Kim Sung, they are called smart materials because they require no controls and no external energy.262

The research that has lead to the Bloom installation and subsequent work with thermo-bimetals by DoSu Studio Architecture has included prototypes to see how the curling action would react to changes in temperature and possibly allow air to ventilate through the system (figure 71). The installation itself is a proof-of-concept project, but gives promise to future applications in architecture: the technique could be used for light control, thermoregulation, or even differentiating between levels of privacy in a building. DoSu Studio Architecture has also started development of building components for the market based on a thermo-bimetal system integrated
Fig. 68
Above: The Bloom installation in the courtyard of the Material & Applications Gallery, Los Angeles, California.

Fig. 69
On the right: Close-up of Bloom showcasing the individual panels.
into glazing panels. When the sun hits the outside of layer of the façade panel and heats the internal cavity, the thermo-bimetal will start to curl and block out the sun in sun-affected parts of the façade. This means that in a large building the whole façade could be differentiated depending on how the sun hits the surface.\(^{263}\)

As mentioned, the Bloom installation is a proof-of-concept project, and as such has been designed to showcase the underlying innovation with its architecture. The orientation of the installation on its original site and the shape of the structure itself has presumably been carefully designed so as to expose it to different light conditions during the day. The biomimetic inspiration behind the work has thus been a deciding factor behind the architecture of the pavilion, and the design does not shy away from showcasing the materiality and the curling function of its elements.

The façade element developed for the general market (figure 74), however, is more of a proto-architectural element in its design. In the Bloom installation, the curling movement of the elements and the subsequent change in the permeability of the canopy are integral parts of the architectural experience. Understandably as the façade element has not yet been subjected to the architectural demands of any one building project, the overall expression is that of a standard glazing unit, though with an innovative and integrated functionality. The differences between these two applications of the same basic principle of a responsive building skin show the architectural malleability of biomimicry as a design tool. Using biomimicry as a tool does not in itself necessarily drive the architecture towards a specific language – the architectural intent comes from the designer.
Fig. 71
On the right: An early diagram of the surface ventilation principle of the Bloom installation.

Fig. 72
Below: Time-lapse sequence of the surface change in Bloom during the course of one day.

Fig. 73
On the right: A closer view of the Bloom installation’s panel system.
Fig. 74
The ‘smart window’ glass panel shutter system concept, an ongoing research project by DoSu Studio Architecture.

Fig. 75
Thermo-bimetal prototyping by DoSu Studio Architecture.
Fig. 76-78
Above: The Homoeostatic Facade System prototype by Decker Yeadon works with similar principles as the ‘smart window’ panels of DoSu. From left to right: the system in its open, transitional and closed phase.

Fig. 79
On the right: Prototype detail of the Homoeostatic Facade System by Decker Yeadon.
14. Case Three

14.1 Identification of analogies

The third case looks at a dynamic strategy manifested as the other of the two major behavioural adaptations in plants, tropisms. Tropisms are active autonomous movements, as they are based on the function of motor organs driven by a change in turgor pressure. The two example projects given here approach the emulation of a flower head’s heliotropism in contrasting ways: the Adaptive Solar Façade (AFS) makes a parallel between heliotropic plants and the elements of the façade system; the second one, the Heliotrope, makes a parallel between a heliotropic plant and the whole building itself. In terms of solar optimization strategies, the AFS takes heliotropism as a strategy for the changing the permeability of the building envelope, whereas the Heliotrope takes heliotropism itself as the dictating concept for the whole architecture of the building. Both of the examples have an approach that is mechanical and highly engineered. The analogy to nature comes from the adaptive strategy, not the functionality of the movement mechanism. The mechanics of heliotropic movement in plants is based on the cell structure of a joint-like pulvinus in the stem of the plant. Motor cells within this section expand and contract based on turgor pressure. A cycle of pressure increases on one side and decreases on the other creates a rotational motion in the stem, which turns the head of the flower over the course of the day.264

14.2 Adaptive Solar Façade

Designer: Team at Architecture and Building Systems, ETH Zürich

Biomimetic principle: solar tracking

Inspiration: heliotropism in plants

The Adaptive Solar Façade (ASF) is a modular, integrated dynamic building façade system developed by a team at the Chair of Architecture and Building Systems at ETH Zürich. The kinetic behaviour as well as the architectural expression of the façade can be controlled through individually addressable modules.265 The first full-scale proof-of-concept prototype was constructed on the façade of the House of Natural Resources building at the ETH Honggerberg campus in 2015 (figure 80).

From an energy management perspective, the envelope of a building acts as a buffer or mediator between the interior and the exterior environment, and this has been the starting point for the project. The envelope can mitigate the effects of solar gains and thus offer reductions in heating or cooling loads, and improve the distribution of daylight. Therefore, they have argued, integrating photovoltaic modules into a dynamic shading system offers the possibility to fine tune the different functions of the façade: generate electricity, and balance the energetic performance with architectural expression. The answer to these aspirations has been presented in the form of the Adaptive Solar Façade.266

The basic element of the AFS is its multifunctional and dynamic module: the module provides shading, energy production, and daylight management. The movement of the modules can be individual or clustered into small groups. Because
On the other hand, thin-film PV modules, such as Cu(In,Ga)Se₂ (CIGS), offer the advantage of flexible, curved, shapes and a lightweight structure when compared to the traditional modules, which come at the price of lower energy conversion efficiencies. However, recent research results have demonstrated that thin-film PV modules can also attain efficiencies similar to the traditional modules (Reinhard et al., 2013). In addition, from an economical perspective, the price per watt-peak of both systems have become comparable. Therefore, thin-film PV systems have become a powerful technology for BIPV (Kaelin et al., 2004; Chen et al., 2014).

The lightweight structure of thin-film modules allows it to consider their integration into the building envelope. Although such facade PV systems receive less irradiation than rooftop and ground installations, they offer lower diurnal and seasonal variations, and can therefore substantially contribute to local electricity generation. Integrating BIPV with conventional building components, such as shading systems, can further lower costs and environmental impacts (Perez et al., 2012).

From an architectural perspective, the building envelope, or facade, is in essence the public face of a building, and has therefore a large impact on the perception of the building. From an energetic perspective, the envelope acts as a buffer or mediator between the interior and the exterior environment (see Fig. 1). The envelope can mitigate solar insolation, thereby offering reductions in heating/cooling loads, and improve distribution of daylight. Therefore, integrating PV modules into a dynamic shading system offers the possibility to fine tune the different functions, generate electricity, and balance energetic performance with architectural expression.

In this paper, we present our current progress on the Adaptive Solar Facade (ASF), a modular highly integrated dynamic building facade. The energetic behavior as well as the architectural expression of the facade can be controlled with high spatio-temporal resolution through individually addressable modules. The novelty of the ASF, compared to other dynamic facade systems, lies in the complexity of the integration of the individual functions, resulting in multidimensional functionalities.
the modules can respond to external stimuli and move independently, complex surface patterns on the façade can be produced. The complexity is generated through its granularity and behaviour rather than through the use of non-standard elements (figure 81). The diamond shaped modules are the result of the current prototype designs, but other shapes could be possible in future designs. The tiling pattern can also be subject to variation. The AFS can also be applied as a retrofitted solution to an existing building, and the design of the modules can follow the architectural language of the existing façade.267

Biomimicry approach

The biomimicry concept behind the AFS is rooted in thermal control and energy management, as well as light control. In the current implementation, the modules of the system are capable of two-axes solar tracking to maximise solar energy harvesting performed by the façade. To facilitate the heliotropism of the panels, a measurement unit that measures the azimuth and altitude angles of the sun is attached to each module. The reference positions for the prototype testing of the orientation of the sun on a given date and time were generated with the solar simulation plug-in DIVA for Rhino (figure 84).268

The general design process for the AFS in each specific building project follows seven steps: selection of position on the envelope, selection of position on the selected façade, selection of support structure (frame, cable, etc.), selection of panel design, selection of grid size and spacing according to the desired shading effect, selection of panel colour and transparency, and selection of granularity of control (single, cluster).269

The AFS prototype described by Nagy at al. consists of four key elements: the photovoltaic shading panel, a soft-pneumatic actuator, a cantilever, and the supporting frame of the system. The soft pneumatic actuator is made of silicone rubber and energized using compressed air. Each actuator contains three inflatable chambers and is capable of orienting the attached panel along two axes (figure 83).270 Even though the design team does not mention a biomimetic inspiration behind the design of the actuator, the presence of one can be argued. A search for the way in which plants actuate tropic movements lead to the function of the pulvinus: the pressure-induced mechanism of the soft pneumatic actuator is analogous to the turgor-pressure induced mechanism of the pulvinus.

The aim of the project is not to use a high level controller to coordinate the functions of the façade, but rather investigate how the system can adapt to its environment and its user. It is noted that typically building occupants do not adjust their blinds more than once a day. This means that as long as the movement of the modules is not distracting and does not contrast with the occupant’s wishes, there is potential for automated control of the façade shading system. However, there is a need for an override mechanism of the automation, in case of a conflict between the needs of the solar energy harvesting optimisation and the occupant’s wishes.271

The energy consumption and saving of the ASF have been compared to two different configurations: a case without shading and a standard louver system with fixed blinds. The total energy saving achieved compared to these configurations were 56% and 25%, respectively.272
Fig. 82
Proof-of-concept prototype of the ASF with 8 panels on a wooden frame. (a) Front view; (b) rear view showing the actuators and cable net structure, and (c) open and closed configurations of the module.

Fig. 83
Kinematics of the soft pneumatic actuator. (a) Deflated actuator. (b), (c), and (d) show the first, second, and third inflated chambers respectively.

Fig. 84
(a) Module shading calculated within Rhino/Grasshopper for a specific sun position. (b) Corresponding rendering using the LuxRender software.

Table 4
Simulation results: net energy demand.

<table>
<thead>
<tr>
<th>Chamber 1</th>
<th>Chamber 2</th>
<th>Chamber 3</th>
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<tr>
<td>Heating (GJ)</td>
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<td>5.29</td>
</tr>
<tr>
<td>Lighting (GJ)</td>
<td>1.56</td>
<td>1.65</td>
</tr>
<tr>
<td>Total (GJ)</td>
<td>19.7</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Simulation results: total electricity demand.

| | Total (kW h) | 430 | 391.8 | 38.4 | 8.9 |
| | Cooling pump (kW h) | 4.17 | 3.24 | 0.9 | 3.0 |
| | LED lighting (kW h) | 124.9 | 121.1 | 3.78 | 22 |
| | Heating (kW h) | 301.2 | 267.4 | 33.0 | 11 |

kgCO2-eq (EU grid mix) 171.7 156.3 15.3 8.9
The first prototype of the proto-architectural product was made without a photovoltaic module, to test the functionality of the soft pneumatic actuators (figure 82). The first full-scale proof-of-concept prototype was constructed on the façade of the House of Natural Resources building at the ETH Honggerberg campus (figure 87). This prototype is 3.9 metres and 3.2 metres in its dimensions, with 50 individually operable modules. The prototype is being used to validate the numerical models and compare the thermal and electrical performance of the ASF to an adjacent an identical room in the same building, but without ASF. The next prototypes will be installed in the High performance–Low energy research and innovation unit (HiLo) at NEST (Next Evolution of Sustainable Building Technologies), a Swiss research and demonstration platform (figure 86). The HiLo unit is planned as a duplex penthouse showcasing ultra-lightweight construction as well as smart and adaptive building solutions, including the ASF (figure 88). The construction on the HiLo unit is currently in progress. 

According to Nagy et al., dynamic facades have the potential to add to the architectural expression of buildings by making the changeable aspects of the environment visible. In this case, as well as in the Freiburg Heliotrope, this is done with solutions that regardless of their biomimicry approach are quite technical in their implementation. The AFS conveys the message on f adaptation to the outside, but has little discussion with the spatial configuration on the buildings it is implemented on. Here it has a stark contrast to the Heliotrope, in which the whole building itself and its spatial organisation is dictated by the heliotropic principle chosen as the biomimicry approach.
5.2. Building scale: ETH House of Natural Resources

Our first full-scale proof of concept prototype, shown in Figs. 20 and 21, was constructed on the House of Natural Resources Building (HoNR) on the ETH Honggerberg campus (www.honr.ethz.ch). The building was inaugurated in June 2015, and showcases advances in sustainable building technology, e.g., post-tensioned timber frame using hardwood, timber–concrete composite slab using beech wood plates, biaxial timber slab, and the ASF.

The ASF prototype is 3.9/C2 3.2 m and contains 50 individually addressable modules. A movie of its construction and operation is available on the website of the authors (http://systems.arch.ethz.ch). The ASF was installed in front of a south facing facade. To monitor the thermal comfort, temperature, humidity and illuminance sensors have been deployed inside the facade. In addition, the adjacent and identical facade with a conventional, fabric based, shading system is monitored. The objectives are to validate the numerical models, compare the thermal and electrical performance of the ASF to the standard facade, and quantify the differences. Furthermore, feedback from the occupants will also be gathered through behavioral studies.

5.3. Outlook: HiLo/NEST

The next prototypes will be installed in the HiLo (High performance – Low energy) research and innovation unit of NEST (Next Evolution of Sustainable building Technologies, nest.empa.ch). NEST is a dynamic, modular research and demonstration platform for advanced and innovative building technologies in Switzerland.

The HiLo unit, shown in Fig. 22, is planned as a duplex penthouse apartment for visiting scientists, and will show-case ultra-lightweight construction as well as smart and adaptive building systems. The Adaptive Solar Facade will be one of four core innovations exhibited in HiLo, the other three being:

1. An integrated, thin shell roof (Veenendaal and Block, 2014),
2. A funicular floor system (López et al., 2014), and
3. An occupant centered control system (Nagy et al., 2014, 2015).

In fact, two ASFs will be installed at HiLo on different facades (south and south-west) in front of the two bedroom windows. This will allow us to study the individual control and interactions of the occupants with the facades, in a residential setting – as opposed to the ASF on the HoNR as an ofi ce setting. The NEST backbone was completed in September, 2015, and the construction of the HiLo module is scheduled to start in mid-2016.

Fig. 20 Building scale ASF prototype on the House of Natural Resources (HoNR).

Fig. 21 Inside view on the ASF.

Fig. 22 The HiLo module at NEST/EMPA will feature two adaptive solar facades.

Fig. 86 Above: Rendering of the ASF at HiLo.

Fig. 87 On the right: Inside view of the ASF at the House of Natural Resources.

Fig. 88 Below right: Rendering of the planned NEXT HiLo.
14.3 Freiburg

Heliotrope

**Designer:** Rolf Disch Solar Architecture

**Year:** 1994

**Biomimetic principle:** heliotropism

**Inspiration:** heliotropic cycle of the Alpine buttercup (*Ranunculus Adoneus*)

The Heliotrope is a live-work building designed by architect Rolf Disch built in 1994 located in the city of Freiburg, Germany (figure 89). Similar Heliotropes have been built in Offenburg in 1994 (figure 90) and Hilpoltstein in 1995. The architect himself describes the project as a solar power plant with a floor area of 180 m² in the ‘top house’, with the possibility of a second living unit located in the basement. According to the architect, the Heliotrope is indeed an energy-producing house, which in regard to its own electricity consumption produces surplus electricity that is then supplied to the public grid.

The main volume of the building is a cantilevered cylinder around a central load-bearing column made of veneered cross-laminated wood (figures 96 and 97). The column has a diameter of 2.9 metres and contains a spiral staircase connecting the living and working spaces over a height of 14 metres. All main rooms are accessible by the stair, so the need for transitional spaces is kept to a minimum (figures 91-95). The column and the building volume itself are 18-edged rather than purely circular, standing on top of a basement level.

The intention of the design has been to produce a plus-energy house with biomimetic solutions. The solutions used in the project can be argued to belong into the categories described above on where to use biomimicry: namely energy management and thermal management. To achieve the set goals, the dynamic behavioural adaptation of heliotropism has been applied. In contrast to the other cases presented in this thesis, the Heliotrope uses the strategy not only in its envelope, but also in the whole building itself.

The rotational heliotropic motion such as that of the Alpine buttercup (*Ranunculus Adoneus*) that grows in the subalpine mountainous region near Freiburg was an inspiration for the architect to apply a design strategy that would optimize passive solar gains as well as the energy harvested by active solar systems. Heliotropism is important to plants like the Alpine buttercup because of the short growing seasons, which makes the optimization of sun angle exposure critical to capturing enough energy for photosynthesis.

The design utilizes the strategy of heliotropism in two ways: first, the whole volume of the building rotates around its central column at a rate of 15° per hour following the sun; second, on the roof of the building is a 54 m² solar panel with a two-axis solar tracking system that turns around the horizontal and the vertical axis. A programmable timer controls the movement of the Heliotrope with weather sensors (temperature, humidity, solar radiation, precipitation, etc.) allowing for a maximum of 180 degrees rotation. According to the architect, by using computer-controlled tracking sequences, the solar panel produces 30–40% higher energy gains compared to a fixed solar system. The benefits of a heliotropic movement are realized through the composition of the envelope of the 10.5 m diameter space. The façade is glazed and opaque on opposite sides of the cylinder. During cooler days, when heating is required, the glazed side is positioned towards the sun, and conversely on warmer days, the insulated part of the building is turned towards the sun to minimize
Fig. 89 Above left: The Freiburg Heliotrope.

Fig. 90
Above right: A Heliotrope showroom and visitors centre designed by Rolf Disch Solar Architecture for Hansgrohe in Offenburg, Germany.

Fig. 91
Below right: Interior view of the Freiburg Heliotrope.
unwanted solar heat gains. The advantages provided by the optimization of solar gains are utilized in the energy systems of the building: the flooring material as well as the water in the floor heating system are used for heat storage of the solar energy falling through the windows onto the floor – control of the floor heating allows the heated water to be pumped to the opposite, shaded side of the building.278, 279

The applied biological concepts in the project have resulted in measurable increases in energy efficiency. Lee and Spiegelhalter argue that the benefits of the applied solutions are the direct result of their inherent link to the site and the local conditions: native biological systems work only with ‘what is available’: variations in plant species are evolutionary indicators of regional variation including solar gains, temperature ranges and water resources. This makes native plants indicators of appropriate architectural responses to local climates.280, 281

In this case, the biomimicry approach has dictated the massing, location on the site, the overall shape of the building, and organisation of the spaces around the central axis of the cylindrical mass. It could even be argued that striving for innovations in sustainability in the form of a biomimetic energy management approach has been the driving force behind the whole design and building project. The applications, however, are quite technical and do not necessarily add to the sensibilities of the architectural expression. There is nothing especially organic or ‘natural in the architecture, instead the building reads like a machine, at least from the outside. There is a striking contrast to the Adaptive Solar Façade – even though both designs are based on the same adaptive strategy of heliotropism, and both are quite technical – only the Heliotrope allows for the biomimicry approach to inform the actual spatial composition of the building.
Fig. 92
On the right: Interior view of the Freiburg Heliotrope.

Fig. 93
On the right: Section of the Freiburg Heliotrope.

Fig. 94
Below left: First floor plan of the Freiburg Heliotrope.

Fig. 95
Below left: Second floor plan of the Freiburg Heliotrope.
Fig. 96
The load-bearing central column containing the staircase.

Fig. 97
The interior of the staircase.
Case studies, references

[250] Ibid., p. 5.
[251] Ibid., pp. 6–7.
[252] Ibid., pp. 7–8.
[253] Ibid., p. 8.
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[278] Ibid., p. 2–3.
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summary
The goal set out in the beginning of this work was to define what biomimicry is and how it could be used in architecture. Natural analogy and the imitation of nature is not in any way a novel phenomenon, and setting the specific approach of biomimicry in the historical and ideological context has been essential in understanding it. The relationship of design and natural inspiration has evolved together with our understanding of nature: the advancements in biological research and earth sciences, and the simultaneous change in the social climate have influenced the analogies drawn. Scientific advancements and the emergence of biology as a modern science from the 18th century onwards have brought new and deeper ways of understanding natural phenomena, and have subsequently also brought new ways of interpreting biological examples in design. This has provided for a shift from vitalist ideals to and predominantly symbolic analogies to those of a more functional approach. With this shift, the mimicking of nature has evolved from the imitation of natural forms and composition to that of abstracting and imitating how nature functions.

In this historical context, biomimicry follows in the line of natural analogy of biotechnics and biotechnique, seeing plants and other natural organisms as inventors to learn from. The analogy is ecological in its essence, taking the way an organism adapts to its environment as the starting point for the emulation. The things to learn from nature are not so much answers to questions beginning with what, but how. How do different organisms regulate homeostasis? How does nature deal with water cycles or thermoregulation? The same line of analogy was later used by bionics, although first in a very anatomical sense dealing with human anatomy, but later expanding to biomimetics and biomimicry. So what exactly is biomimicry in architecture? It is sustainable solutions achieved through the emulation of nature. It is answering questions of how should we design buildings, how should we build, and how to solve technological problems by asking: “How does nature do it?”

Biomimicry is not a science in itself. Biomimicry is shaped by the fields of science relevant to the study of natural examples. Its focus is dependant on the intentions, field of work, and the methods of the person using it. It means an attitude of accommodating curiosity towards the phenomena and laws of the physical environment that architecture is a part of. In the field of architecture, the focus is on carefully considering the functional qualities that are being sought after with biomimetic solutions, and the architectural intentions and expression of the designer.

The most challenging task in this work has been to make the distinction between biomimicry and biomimetics. What we have established is that biomimicry is a broad approach of emulating nature by using biomimetic solutions. Biomimetics has an emphasis on the ‘engineerability’ of solutions to direct and physical challenges, whereas biomimicry aspires to solve indirect and systemic challenges as well as direct ones, always striving for sustainable and resilient solutions and a ‘natural balance’. In this interpretation, biomimicry employs a kind of compositional interpretation of organic analogy as well as an ecological analogy, as it takes nature as an example of a ‘wholeness’ and balance one should strive towards, whereas biomimetics works only with a functional interpretation of mostly ecological and anatomical analogies. Biomimicry takes Nature as model, measure and mentor.
The distinction made in this thesis, however, is not settled in the general discussion of biomimicry, and the two terms continue to be used interchangeably in some instances. What is important is to acknowledge this condition and make sure that whenever we are discussing biomimicry and biomimetics, we understand the terms similarly.

The modern relationship between human and nature in design is troublesome. Everything we design and build affects the environment, and arguably usually in a negative way. We harvest materials and destroy wildlife habitats, we cut down forests and pump oil to produce energy to our growing demand, and change the micro- and macroclimates all while doing it. This action shows an attitude towards nature that is characterised by human domination. Yet, the relationship is in truth the opposite: nature dominates us. We cannot escape the laws that govern the delicate balance of natural systems because we are part of those systems. Sustainability is becoming the norm in architecture, and biomimicry can be a valuable tool in the designing of solutions and systems that work with the environment instead of against it.

Setting aside the argument of sustainability, biomimicry can also serve as an inspirational catalyst in the design process. A biomimicry approach can help the architect evaluate the design and its boundary conditions from a perspective that might not present itself in a ‘traditional’ design process. Biomimicry can lead to innovations – technical or spatial – that would otherwise not arise. It is the architect’s job then to make these innovations part of the desired architecture.

One of the biggest challenges of biomimicry is the anecdotal nature of its successes: a lot of information is available in the form of case studies, and not as a theoretical basis for a way of designing. There are guidelines proposed by researchers and biomimicry advocates, but they are not specific to any particular design problem. Of course, that is an impossible feat, as not one situation is like the other and as argued before, biomimicry is shaped by the focus of the researcher or designer. The anecdotal existence of successes in the field serves as confirmation of Vogel’s criticism of the subject: successful biomimicry is coincidental or accidental – best achieved when theoretical knowledge is scarce. Paradoxically, this criticism serves as a powerful advocate for biomimicry in architecture: an architect must have basic knowledge of all the fields building design encompasses, from structural design to thermoregulation, but cannot possibly be the expert in any one of the fields. This makes the architect the ideal biomimicry student, with a wide scope of curiosity and a drive for innovative solutions. However, it must be remembered that biomimicry is not an approach that can be successfully pursued without the collaboration of life science specialists.

The most important prerequisites to successful biomimicry are understanding the underlying principles of what is being emulated, a sufficient level of abstraction before the implementation, understanding the differences between nature’s way of building and human technology, and working with sufficient information from life sciences.
The categories for possible biomimetic applications presented here are a rough categorisation of solutions applicable to architecture. Structures, materials, zero-waste systems, water management, thermal control, and energy management all play a role in the building process as well as maintenance, and in the way a building works not only as a system, but also as a part of larger systems. In a decidedly architectural context one can find inspiration in how nature works with light, patterns, and enclosure. There are as many possible innovations as there are architects and design tasks, and the examples given in this thesis of the use of biomimicry are meant as inspiration.

What all of the proposed areas of application have in common is a pursuit of resource efficiency and economy, and optimisation of structures and function. However, in addition to the utilitarian aspects of applying biomimicry, biomimicry could and should also be used to enhance architecture and the experience of space itself. When applying a biomimicry approach to the aforementioned areas, the solutions should be viewed through the lens of and evaluated against the goals of architectural expression.

The Biomimicry Design Cycle presented in this thesis serves as a rough guide to the architect wishing to pursue biomimicry. It helps the designer to identify the goals they are after and the phases to through in getting there: either starting from a technical problem and proceeding through abstraction of biological analogies and their implementation towards the final architectural expression; or beginning with an idea of a spatial experience that can then be processed as an amalgamation of ‘technical problems’. Either way, the process is cyclical and the architectural expression and biomimetic performance of any given solution are interdependent. The process of biomimetic research is pulled by the architectural ambitions of the designer, but until the abstraction of the desired performative quality from the biological model is made, the possible directions of the architectural design are pushed by the qualities of the biomimetic role model. When a level of sufficient abstraction is achieved, the interaction is reciprocal: the abstraction of the biomimetic role model leads to certain boundary conditions within which the architectural expression is established.

The development of the Biomimicry Design Cycle has been very helpful in understanding how to apply biomimicry in one’s own architectural practice. Hopefully it can provide insights and serve as a starting point to others looking to apply biomimicry in their design.

The case studies presented have shown that even when working from a similar source of inspiration, the design process can lead to very different results and architectures. The architect has to be aware of the role and emphasis assigned to biomimicry, and whether the emphasis in the design cycle is on the architectural expression or the technical problems to be solved. Is the morphology emerging from the biomimetic process something to be celebrated and even exaggerated, or is it to be downplayed and subject to some other architectural and stylistic sensibility? Neither one of the options is right or wrong, but simply produce different architectures.

In general discussion, the word biomimicry often evokes images of biomorphic shapes or something vaguely ‘green’. Biomorphism or ‘green’ architecture, however,
is not the always the result of a biomimicry approach, nor should a biomimetic design process lead to any predetermined architecture. The biomimicry approach does not need to be visually recognisable in a building’s architecture, but most importantly in the architect’s intent and process, and the resultant functional qualities of the design. Nevertheless, to promote the benefits of biomimicry, it can be advantageous to express this intent in the architectural expression, even if it does not need to be the most prominent aspect of the architectural language to be used or the most important thing to express.

Biomimicry in architecture is still in search of its focus. Biomimetics has had more emphasis in literary and research, perhaps due to the longer use of the term in engineering, or the more quantifiable nature of the success in ‘engineerable’ problems. Biomimicry, with its emphasis on both environmental and societal sustainability, is more difficult to grasp and promote. However, as the design world and building industry are steadily moving towards the direction of sustainability as a norm, biomimicry will have a stronger foothold in showing what is worth building, and more importantly, how. After more than 3.8 billion years of evolutionary research and development work done by nature, we humans have a lot to learn from.

Our modern relationship with nature, one characterised by human dominance, is not a given. The relationship, or rather our interpretation of it, is in constant flux. It has ranged from the ideal of the inherent goodness of nature and the organic as something divine, to that of trying to understand the natural laws that govern it, to that of imposing our dominance on nature and exploiting it. In recent times there have been some signs of a shift towards a new form of relationship, where humans as a species could find a balance with nature: stop fighting against its forces and instead work with them. The surge of interest in biomimicry is one of those signs. The true relevance of biomimicry in terms of sustainability will be decided by future generations, but for now there is no reason not to embrace such an inspiring and innovative design approach.
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Figure 1. Natural analogy in architecture. Image: Author's own illustration.

Figure 2. Elevation of Santa Maria Novello by Alberti, completed in 1470, showing proportional relationships. Image: Franco Borsi, source: http://www.operasantamarianovella.it/wp-content/uploads/2015/08/5-1-alberti-santa-maria-novella.jpg (accessed August 2016).

Figure 3. Caryatids of the Erechtheion at the Acropolis in Athens, Greece. Image: Wikimedia Commons user Psi guy, Creative Commons Attribution-Share Alike 3.0 Unported (CC-BY-SA-3.0-migrated), source: https://commons.wikimedia.org/wiki/File:Porch_of_the_Caryatids_at_Athenian_Acropolis.JPG (accessed July 2016).


Figure 5. The form of Eero Saarinen’s TWA Terminal at John F. Kennedy Airport, New York (1962) evokes thoughts of flight with its allusion to birds’ or beetles’ wings. Image: Acroterion (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], source: https://commons.wikimedia.org/wiki/File%3ATWA_Flight_Center_2015_NY2.jpg (accessed July 2016).


Figure 8. Acropolis site plan. Image: uncredited, source: http://www2.warwick.ac.uk/fac/arts/classics/students/modules/greecereligion/database/clumca/site_plan.gif (accessed September 2016).


Figure 12. Viollet-le-Duc, Cathédrale idéale, source: http://www.encyclopedie.bseditions.fr/article_complet.php?pArticleId=4&articleIdLib=1%492Alsace+gothique (accessed August 2016).


Figure 15. The underside of a Victoria regia leaf. Image: Biodiversity Heritage Library, Creative Commons License Attribution 2.0 Generic (CC BY 2.0), source: https://commons.wikimedia.org/wiki/File:Victoria_regia_or_The_great_water_lily_of_America_(Plate_3)_(9100782640).jpg (accessed August 2016).


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Figure 19. Fallingwater, the Kaufmann residence by Frank Lloyd Wright. Image: Esther Westerveld, Creative Commons License Attribution 2.0 Generic (CC BY 2.0), source: https://commons.wikimedia.org/wiki/File:Fallingwater_(Kaufmann_Residence_by_Frank_Lloyd_Wright)_-_26_June_2012.jpg (accessed August 2016).

Figure 20. Aldo van Eyck’s Amsterdam’s Municipal Orphanage (1957–60) is an example of structuralism with its clearly defined modules in a more or less flexible arrangement. Image: CCA Mellon Lectures, source: http://www.archdaily.com/151566/ad-classics-amsterdam-orphanage-aldo-van-eyck/50380ed428ba0d599b000bcb-ad-classics-amsterdam-orphanage-aldo-van-eyck (accessed April 2017).


Figure 22. A bionic hand with a skeletal structure modelled after the human hand. Image: bebionic, source: http://bebionic.com/the_hand/technical_information (accessed August 2016).


Figure 24. The sponge Euplectella and the leaves of Tipiana tipu as an inspiration for the Spiral Bridge by Dennis Dollens and Ignasi Pérez Arnal. Image: Dennis Dollens and Ignasi Pérez Arnal, source: http://workgroups.clemson.edu/AAH0503_ANIMATED_ARCH/linked%20docs/DennisDollens_DesignBiomimetics.pdf (accessed August 2016).

Figure 25. An illustrative example of contemporary organic architecture is Sir Peter Cook and Colin Fournier’s Kunsthaus Graz, completed in 2003. Image: Marion Schneider & Christoph Aistleitner, Creative Commons License Attribution-Share Alike 2.5 Generic (CC BY SA 2.5), source: https://commons.wikimedia.org/wiki/File:Graz_Kunsthaus_vom_Schlossberg_20061126.jpg (accessed August 2016).


Figure 27. The Bosco Verticale in Milan by Stefano Boeri Architetti is an example of architecture that can be dubbed both ‘green’ and sustainable. Image: Stefano Boeri Architetti, source: https://upload.wikimedia.org/wikipedia/commons/a/ac/Stefano_Boeri_Architetti_-_Bosco_Verticale_-_Drawings_05.jpg (accessed April 2017).

Figure 28. Overview of the basics and objectives of ‘Architektur-Bionik’, or architectural biomimetics. Image: adapted from J.S. Lebedew in Architektur und Bionik (1983), page 20.

Figure 30. The web of a Cyrtophora citricola, also known as the tropical tent-web spider. Image: Olaf Leillinger, Creative Commons License Attribution-Share Alike 2.5 Generic (CC BY SA 2.5), source: https://commons.wikimedia.org/wiki/File:Cyrtophora.citricola.net.7626.jpg (accessed August 2016).


Figure 32. The interior of the Crystal Palace, not inspired by the water lily, but a feat of modern engineering. Image: Victoria & Albert Museum (public domain), source: https://commons.wikimedia.org/wiki/Crystal_Palace#/media/File:Kristallpalast_Sydenham_1851_innen.png (accessed April 2017).


Figure 34. Bamboo culm cut-away section showing how the otherwise hollow stem is strengthened in the nodes. Image: Bamboo Botanicals, source: http://www.bamboobotanicals.ca/img/about-bamboo/culm-section-lg.jpg (accessed April 2017).


Figure 36. The structureFIT process works in three phases to find a satisfying structure: problem setup, exploration and refinement. Image: Caitlin Mueller and MIT. Screen captures from the structureFIT website, source: http://digitalstructures.mit.edu/page/tools (accessed April 2017).


Figure 38. The hierarchical structure of the Euplectella aspergillum. Image: http://science.sciencemag.org.libproxy.aalto.fi/content/309/5732/275/F1 (accessed October 2016).

Figure 39. The Mine the Scrap software will scan the scrap pieces available and adapt the structure according to the preferences of the designer. Image: Certain Measures, source: http://certainmeasures.com/mts_software.html (accessed April 2017).


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Figure 43. The Hammarby model of energy, waste and water treatment, a forerunner in the design of an urban area with ecosystems thinking and water management. Image: Lena Wetterén, Bumling AB, source: City of Stockholm (2011) About Hammarby Sjöstad, Online at: http://bygg.stockholm.se/Alla-projekt/hammarby-sjostad/ (accessed March 2017).


Figure 47. The Eastgate Center and its cooling system inspired by termites’ nests. Image: Mick Pearce, source: http://www.mickpearce.com/biomimicry.html (accessed April 2017).

Figure 48. The linear abstraction process according to Knippers and Speck. Image: Author’s own illustration, adapted from Knippers and Speck (2012), p. 6.

Figure 49. The Biomimicry Design Lens, Biology to design. Image: Biomimicry 3.8, source: https://biomimicry.net/the-buzz/resources/designlens-download-2/ (accessed: March 2017).


Figure 51. The Biomimicry Design Cycle. Image: Author’s own illustration.


Figure 54. Introducing system feedback loops: If A causes B, can B also cause A? Image: Author’s own illustration.

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Figure 60. Simple physical model as a first-level abstraction of the kinematic system. Image source: Knippers and Speck (2012), p. 7.

Figure 61. The kinematic principle of the Yeosu facade, further abstracted from the principle of the Flectofin. Image source: Knippers and Speck (2012), p. 7.

Figure 63. Prototype of the facade shading system based on Flectofin. Image source: Knippers and Speck (2012), p. 7.


Figure 66. Abstraction and transfer of the biological principle of shape change induced by hygroscopic and anistropic dimensional change. Image: Achim Menges, source: http://www.achimmenges.net/wp-content/gallery/frac_hygroskin_02_lowres/HygroSkin_2_02.jpg (accessed March 2017).


Figure 72. Time-lapse sequence of the surface change in Bloom during the course of one day. Image: DoSu Studio Architecture, source: http://www.grahamfoundation.org/grantees/3972-bloom (accessed April 2017).


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Figure 80. A concept image of the ASF showing the modules on a building facade, mounted in frames on a cable net structure. Image: Nagy et al. (2016), p. 144.

Figure 82. Proof-of-concept prototype of the ASF with 8 panels on a wooden frame. a) Front view, b) rear view showing the actuators and cable net structure, and c) open and closed configurations of the module. Image: Nagy et al. (2016), p. 153.

Figure 83. Kinematics of the soft pneumatic actuator. a) Deflated actuator. (b), (c), and (d) show the first, second, and third inflated chambers respectively. Image: Nagy et al. (2016), p. 148.

Figure 84. a) Module shading calculated within Rhino/Grasshopper for a specific sun position. b) Corresponding rendering using the LuxRender software. Image: Nagy et al. (2016), p. 152.


Figure 87. Inside view of the ASF at the House of Natural Resources. Image: Nagy et al. (2016), p. 154.

Figure 88. Rendering of the planned NEST HiLo. Image: ETH Zürich source: http://www.systems.arch.ethz.ch/research/nest-hilo/_jcr_content/par/fullwidthimage/image/imageformat.fullwidth.50421005.png (accessed April 2017).


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