Chapter 3
Biomimetics for Buildings

Our technology-oriented economic world has only relatively recently discovered the functionality and esthetics of natural forms and structures. However, people of all cultures have already intuitively used the functioning principles of nature: storing water in terraced fields, using wind for the separation of chaff from the wheat, or natural climate control in living spaces in earthen houses with updraft cooling in hotter regions. In addition, most functions in nature are closely linked with a sign-emitting, physical manifestation. Success by attraction (i.e., flowers and their coloration, which lure insects by attraction for pollination) depends on these functions.

> …In spite of this, we still build buildings counter to nature from the past epochs. Our times demand lighter, more efficient, mobile, adaptable, or, in brief, natural houses. … This consequently leads to the further development of the lightweight structure, of the building of cells, shells, sails, and airborne membranes. (Frei Otto)

What does nature teach about form and function? Natural life forms distinguish themselves by their multifunctional conceptualization of building parts and functioning groups for the most various demands: envelopes, warmth, thermoregulation, energy production, structure, enclosure, unfolding processes, transportation, movement, and growth. These are only some of the tasks that are fulfilled by nature among innumerable examples and variations. These “technological” developments of life are responses to laws of physics and chemistry, to the necessities of growth and reproduction, and to reaction and utilization. Nature has accordingly created and optimized products whose marketability has been tested and whose “product profile” has been honed and suitably configured for its niche. The results of their developments would be listed in a book of examples or guidelines for successful management, if nature indeed needed one.

Architects must also navigate a multitude of demands comparable to nature, but additionally they must deal with the difficulties of creative implementation as well. Constraints to design result from materials, which can merely fulfill *one* purpose (either structure or shelter), or even from the clients and purchasers of buildings themselves, whose demands (“only beautiful”) sometimes further restrict the process. Integrative design means handling a wide variety of requirements within the

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project with intelligently behaving materials. For architecture, this process also means fulfilling of esthetic sensibilities as part of their general public duty for finding an appropriate design for the collective urban environment.

3.1 Architecture and Biomimetics from the View of Architects, Engineers, and Designers

Architecture must serve the people. All structures—perhaps with the exception of monuments—have to fulfill a functional purpose; monuments fulfill at the very least the purpose of remembering. As a result, a social duty is conferred onto every structure. They perform this function more or less dutifully, be it in consideration of the function to be provided or in its form. For the consideration of the issue of "design" the following essential questions could be posed: What is the effect in relationship to the beholder? Which duties belong to the artificial interpretation of our environment? What consequences arise from understudied designs and what kind of self-image is implanted by such neglect?

From the global changes to cities due to the lack of social awareness emerge "Simcity"-like urban spaces without vision or quality, with pre-programmed potential for violence and questionable sustainability. Global change does not only stop at the built environment. The global change in cities and, as a result, their formation is not only an economic, social, urban challenge but also above all a cultural one. In his conclusion from "Aus Krise zu Innovation" (From Crisis to Innovation), the architecture theorist Philipp Oswalt pointed out:

> The debate over the crisis of shrinking cities is currently an impulse for the development of new concepts and models. The starting point of the classic modern movement was quite similar.

For classical modernists it was not only about the development of a new architectural style or urban typology, but also about the future-oriented understanding of design and "ultimately a new model for society." The approach of biomimetics similarly aspires to a new societal model: Technology is not to be used as an end in itself, but it must be integrated into a cycle, in which the efficiency of energy use and material application is considered as a given, as nature would teach us.

It would then be too easy to simply relate the precedents of nature to the forms of our structures. Biomimetics is not merely a stylistic form in which one visually perceives a quasi-natural origin in building shape—often represented by rounded forms ("biomorphic"). Biomimetics instead implies the previously formulated structural and functional chain of "abstraction, interpretation, and application of insights" from biology to technology; only then can a form emerge.

In what manner then have the structures of humans found themselves in relation to natural structures? Human beings are accustomed to suitably adapting themselves to the conditions of their environment. In this manner they cannot wholly differentiate themselves from other living beings, such as beavers, which can form entire lakes with their dams, or termites, which construct complex structures with thermoregulating functions. What differentiates human beings from these organisms is then, among many other aspects, the deliberate construction and continual development of their technological products. A prominent product of their creative ability is of course the building of houses, the development of architecture. The human being consciously erects structures that must serve a whole variety of selected purposes. They fulfill the requirements of protection from weather, protection from enemies, and security. The dwelling also offers, as locale for communication, spaces for meeting, and, as place of protection, the possibility for retreat from society. Human beings have adapted their dwellings for further purposes: for the purpose of communal activity, for the purpose of recovery, of enjoyment, for the storage of supplies, for the practice of religion, and so on. The complete, differentiated design of these spaces is an artistic act of creativity that only humans can accomplish. For this purpose they use their ability to develop technologies. Technologies and their devices were initially developed by humans to overcome physical shortcomings: Spears and stone axes were needed for hunting, as they are not fast enough, or to defend themselves, as they are not strong enough. Owing to the lack of effective fur against the cold, humans at first considered the use of primarily hunted furs from the animal kingdom. Later they began to produce their own material for the desired effects of warmth and moisture protection. They used manufactured materials as a second skin—as replacement fur—and as a third skin as well, their dwellings. However, it is due to lack of technological advancement in the design of this third skin that places humans right at the beginning of development compared what nature has already performed, namely the energy and substance-sparing implementation of multifunctional materials.

Today houses that tend to distance themselves from natural conditions are still being planned and built: instead of reduced sun infiltration and better air circulation, they are regulated with central air conditioning; and instead of conserving the same solar warmth in the winter, they are heated. Many can only perform one or the other. Often the building must be completely sealed to function efficiently with central heating or cooling, or it is too drafty. Natural structural precedents are in every sense more "intelligent." They combine several functions in one structural method. For multifunctioning capabilities biomimetics can provide many inspirations and precedents, so that in the future modern building skins will be able to combine many functions, each according to needs such as protection, warmth, and light (as with polar bear fur). In this manner, building envelopes will be able to produce energy and convey materials similar to leaves, and additionally be structural and able to grow like the skin of an elephant.

The "new concepts and models," of which Oswalt wrote, are to be interpreted within the general belief that technology must not only be developed for the sake of "forward" advancement alone, but should also have the ability to rediscover the multitude of preexisting ideas from nature with the application of biomimetic ideas. The design world can in turn be provided as an enormous technological and artistic spectrum and, if nothing else, the meaningful relationship to their precedents from nature.

3.2 Historical Background and the Origins of Building

Nature offers an inexhaustible arsenal of examples for "living structures" that recall architecture in form and function. These structures have not only inspired architects today but also in the past centuries. According to his story, Brunelleschi (1377–1446), the famous architect, builder, and artist of the Renaissance, was inspired by the form of a chicken egg for the design of the dome of Sanra Maria del Fiore in Florence. Leonardo da Vinci (1452–1519) is also naturally assumed to have more or less investigated nature and have attained his inspirations in this analytic manner.

At the beginning of the twentieth century the structures of the Art Nouveau era had begun to imitate nature with floral patterns and curved building volumes. Artists and architects were inspired by the publications of the biologist Ernst Haeckel in Jena. Haeckel had intended with his studies and publications to argumentatively support Darwin's theory of evolution. However, he developed no functional morphology and instead depicted the various forms of nature more in the manner of an art historian and in the order of ornamentation. Haeckel's sensational books, such as *Art Forms in Nature* and *Art Forms of the Ocean*, managed to obtain global influence even in America and are today in their original form sought-after rarities. An example for the application of "natural" art forms and the orientation to ornament is the entrance gate to the 1900 World Exhibition in Paris by René Binet, which is based on a radiolarian skeleton. Architects today have overcome this glorified natural romanticism, which had then been singled out and characterized in the literature

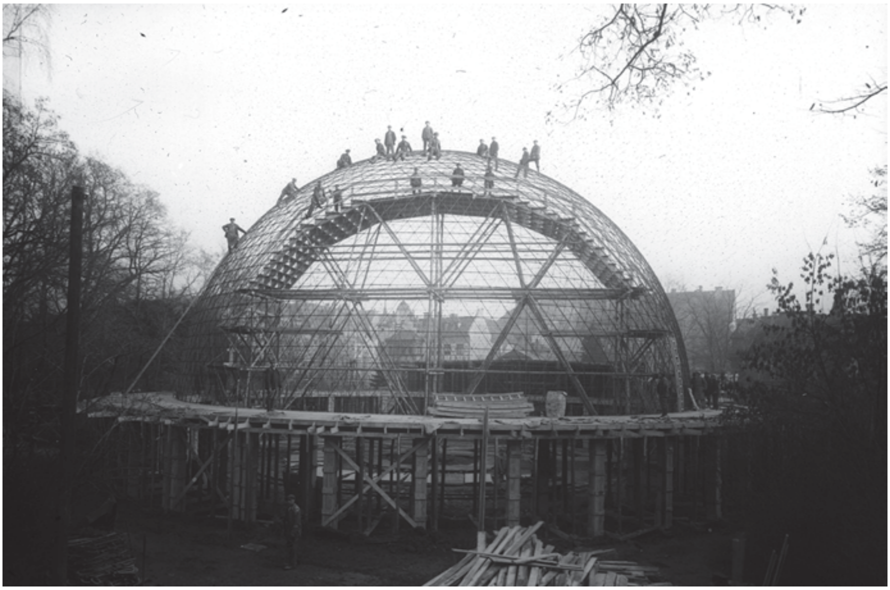


Fig. 3.1 Planetarium Jena, 1942–1925. (Design: W. Bauersfeld, Dyckerhoff and Widmann, Photo University of Jena, Planetarium)

as so-called “bionic building art” and superficially correlates to ornamentation and formalism. Architects increasingly understand the complexity of natural structures and how they can function as sources of inspiration.

The American engineer Buckminster Fuller is one of the most well-known engineers, who had already occupied himself in the 1950s with mechanisms of biological systems and their effects. Fuller’s most well-known trademark was the geodesic dome, one of which he erected for the 1967 World Exhibition in Montreal. This construction typus also recalls, with its delicate, with their delicate, materially minimal construction, skeletons of single-celled radiolaria, which Haeckel had previously investigated. An earlier dome, forerunner so to speak and inspiration for Fuller’s lightweight structures, was constructed for a planetarium building for the firm of Carl Zeiss in 1924–1925 at the former workplace of Haeckel in Jena, Germany. The three-dimensional (3D) spatial framework was subsequently poured out with concrete (Fig. 3.1).

3.3 Definitions and Methods of Biomimetics for Buildings

Different definitions of biomimetics and building biomimetics circulate in publications that often pertain but also sometimes lead to major misunderstandings. To combat this confusion, guideline committees have been set up by the VDI—the Association of German Engineers—that have described the differently used terms. These and current definitions, such as the term “building biomimetics,” are subsequently recorded here. Various methods as to the application of biomimetics are also used, the most of important of which are listed here.

3.3.1 Definitions from the VDI

The VDI, the Association of Gerrman Engineers, does its work in a certain manner, where one is to investigate into regulations that are, in the European countries, usually to be seen as state-of-the-art. The VDI has occupied itself for some time with the issue of biomimetics in its important committee work for the definition of standards. VDI guidelines for biomimetics have recently been developed, the first of which appeared in 2010/2011. The framework guidelines for biomimetics VDI RL 6220 and the VDI RL 6226 Architecture, Engineering, Industrial Design, both of which were developed with the participation of G.P., chairman for the VDI 6226, define biomimetics as

> The interdisciplinary combination of Biology and Technology.

The goal of biomimetics according to the VDI definitions is the

> Abstraction, transfer, and application of knowledge gained from biological models.

This occurs, according to the VDI definition, in interdisciplinary collaboration.

3.3.2 Methods of Biomimetics

The scientific community has solidified two approaches as methods of biomimetic process for buildings, which differentiate themselves by their starting points, as well as a third approach that represents a combination of the two.

One of these methods considers a course of development from biology: Technological developments are stimulated from insights of biological research, push started so to speak ("*Biology Push*").

The other method is driven by a technical scope, in which approaches to solve technical problems are sought within biology, thus extracting then the biological approach to improve an already mostly existing technological product ("*Technology Pull*").

A third method, which makes use of already pursued insights, must also be emphasized within the context of this publication. Building and architecture fields, which are oriented on a quick generation of knowledge, cannot afford research before the construction of each individual building. These fields differ from more linear industries that follow the development process of research → development → serial production and better suited for the continual construction of new prototypes. They use a constantly changing combination of thousands of different solutions to materials and functions for the purpose of developing new design ideas. Biomimetically interpreted, this means that what is considered as advantageous for building and architecture emerges from a pool of "pre-researched" biological and analogous technological mechanisms. The evaluation of which is the methodological approach of "*Pool Research*."

W.N. used the following labels in his epistemology-based book *Bionik als Wissenschaft* (2010) ("Biomimetics as Science"):

"Biology Push": "a discovery in biology is the starting point." ("What could one improve in the area of technology with the help of a certain biological finding?") (p. 196, 197)

"Technology Pull": "The posing of a problem from technology is the starting point." ("Which findings from the living world could help solve a technological problem?") (p. 198, 199).

"Pool Research": "pooling of information." Filling of the biological data reservoir, from which one can draw information for a technological problem. (p. 156).

These labels are also borrowed for W.N. and A. Wisser (2012). The three brief descriptions selected here implement these exact labels as key phrases.

3.3.3 Biology Push and Technology Pull as Methods of Biomimetics

The processes of development according to biomimetics can either be pushed by biology or pulled by a technological product. These processes can then be referred to as "Biology Push" ("Bottom Up") and "Technology Pull" ("Top Down"), respectively.

The contrast between these two approaches drives research in both fields. With "Biology Push," the biological discoveries are the basis for the development of new, technological products. The direction of development runs then from the knowledge and data of biology to the formulation of an idea and development of a technological product. With "Technology Pull," an existing technological product obtains new and improved qualities by the interpretation and application of biological principles. In this case, the direction of development results from a request from the technical world for biology—in the form of the question "Are there comparable approaches in biology to solve this problem?" On the basis of this question, "ideas" are sought in living nature, which could then give an impetus to the technological side and help lead to new or improved products.

3.3.4 Pool Research as Method of the Biomimetic Process for Architects, Civil Engineers, and Industrial Designers

This third method comprises the collection of fundamental knowledge from biology to better understand biological functions with the goal of technical application, without however needing to immediately determine what that application might specifically be (compare Fig. 3.2). In the discussions for the VDI guideline VDI 6226, the following was ascertained:

> For this reason, the design and the development of solutions in building construction and industrial design seldom follow predictable combinations of rational and subjective aspects. Biological models can be integrated into this process at various stages, as a result of which the fields of building construction and industrial design differ significantly from most other technical disciplines with a more unidirectional orientation.

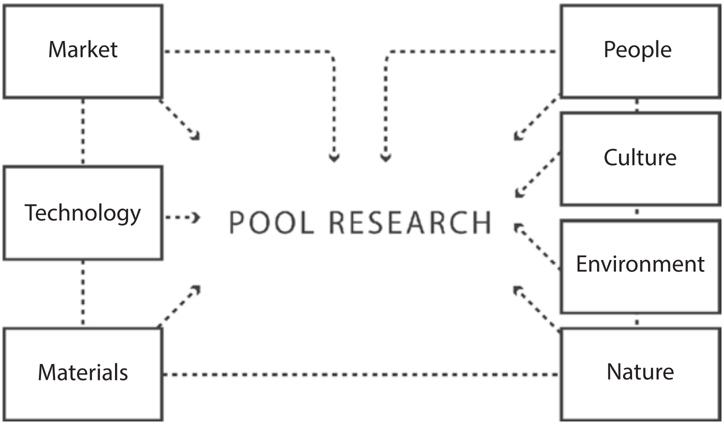


Fig. 3.2 Pool Research analog VDI guideline 6226. (Courtesy of Göran Pohl, Pohl Architects) Figure Translation: Market, People, Culture, Environment, Nature, Materials, and Technology

In this respect, this method does not befit the definition of either of the two previously addressed work processes. Biomimetics is not looked upon in the building and design worlds as a distinct discipline but as a *creative tool*. The insights and knowledge can both be abstracted and described in great detail as well. Frei Otto attempted to understand the functional bases of natural forms and building processes in collaboration with biologists, for example, the botanist Johann-Gerhard Helmcke or the zoologist Werner Nachtigall and other experts, and demonstrated as well how essential the basic fundamentals can be for the further, and often much later, development of biologically inspired structures. In contrast to the "*Biology Push*" and "*Technology Pull*" methods, the "Pool Research" method does not necessarily or immediately underlie an interest for abstraction and application. Instead, the knowledge generation itself is the core of the process and conduct. This result can then be directly or indirectly followed with a technical application or as a whole lead to a discovery of an area for a potential application.

The process of "Pool Research" can follow different paths. One possibility is extraction of knowledge from an in-depth study of a biological precedent from the "pool," which could at some point drive a biomimetic development. A driving inspiration often only emerges in the linking of knowledge to functions in biology; sometimes even years later, namely when the technology has "matured" and the question or issue can be properly formulated (comp. Hill, B. 1998).

Often with the "Pool Research" method analogous technological functions have already been compared with the insights into biological processes, resulting in a tabular register of (both technical and comparable biological) examples and function details, a so-called morphological box. The insights are then evaluated according to these morphological categories and can lead to new "biomimetic" solutions.

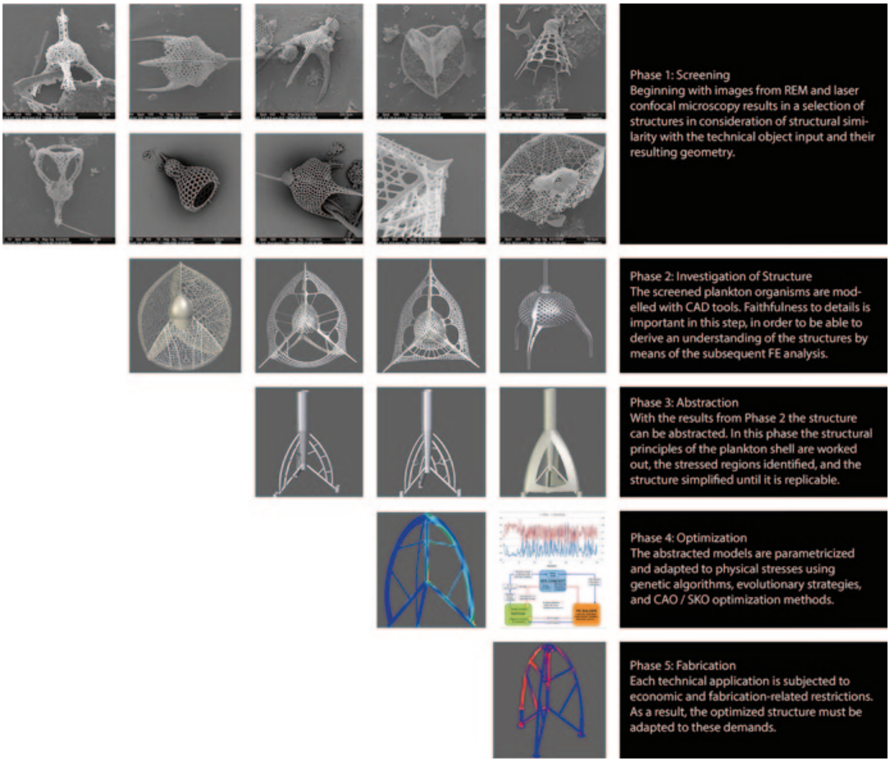
In this manner, "Pool Research" is a strategy for abbreviating the duration of the development process. The insights derived on the basis and means of "Pool Research" are of interest for architects, engineers, and industrial designers who can generate ideas on a broader basis and determine potential courses for realization.

The research project "BioSkin" of the Austrian Institute of Technology (AIT), under the leadership of S. Gosztonyi, explored the potentials of biomimetics in a basic study for the "House of the Future." The research potentials for biomimetic-inspired and efficient facade technologies are described in Sect. 6.29. In Sect. 6.30, the use of daylight is addressed, as well as shading as it relates to the ridge forms of cactuses. This process of investigating fundamental problems using natural examples is a good testament for the effectiveness of "Pool Research," essential for architecture.

3.3.5 Evolutionary Light Structure Engineering (ELiSE)

Evolutionary Light Structure Engineering is a method for the development of optimized lightweight structures.

At the Alfred Wegener Institute in Bremerhaven, Germany, a method that enables a systematic and effective development of form-optimized geometries based



Phase 1: Screening
Beginning with images from REM and laser confocal microscopy results in a selection of structures in consideration of structural similarity with the technical object input and their resulting geometry.

Phase 2: Investigation of Structure
The screened plankton organisms are modelled with CAD tools. Faithfulness to details is important in this step, in order to be able to derive an understanding of the structures by means of the subsequent FE analysis.

Phase 3: Abstraction
With the results from Phase 2 the structure can be abstracted. In this phase the structural principles of the plankton shell are worked out, the stressed regions identified, and the structure simplified until it is replicable.

Phase 4: Optimization
The abstracted models are parametricized and adapted to physical stresses using genetic algorithms, evolutionary strategies, and CAO / SKO optimization methods.

Phase 5: Fabrication
Each technical application is subjected to economic and fabrication-related restrictions. As a result, the optimized structure must be adapted to these demands.

Fig. 3.3 Phases of ELiSE. From above to below: screening, structural study, abstraction, optimization, and fabrication using the example of an off-shore mast. (Courtesy of Christian Hamm, IMARE)

on studies of plankton shells was developed (Fig. 3.3). In this method, the plankton shells are identified with the aid of various search techniques, and after biomechanical examinations and finite element (FE) simulations and calculations, they are evaluated, abstracted, and adapted to structural stress situations and restrictions due to fabrication with the help of methods such as parametric optimization of genetic algorithms.

Using ELiSE, information and data are drawn from unique collections of samples and preserved specimens (Hustedt Laboratory for Diatom Research), as well as a 3D databank of concrete, pre-optimized lightweight structures (parametric computer-aided design (CAD) models and microscopic data). The technical application is supported by the foundational research in the areas of evolution, biomechnanics, diatom taxonomy, and genetic algorithms.

A function-optimized derivation of a completely new and diverse structures and geometries for the development of technical lightweight structures results in the process. The ELiSE process has been implemented in the areas of automobile design, air and space industry, medicine, offshore structures, civil engineering, industrial housings, and consumer goods.

3.3.6 Technical Biology, According to the Definition of VDI

Next to the terms “bionics” or “biomimetics,” the term “technical biology” is often used in the literature.

VDI 6220 explains in Sect. 5.4 that the term “technical biology” was introduced by Werner Nachtigall as a complementary term to biomimetics. Technical biology comprises the analysis of form–structure–function correlations of living organisms with the aid of methodical approaches from physics and engineering sciences. “Technical biology” is thereby the starting point of many biomimetic research projects, as it allows us to have a deeper understanding of processes of biological precedents on a qualitative level and then can initiate an implementation process for a technical application in a suitable manner. Technical biology is, according to N.W., an essential facet of basis research, because “where nothing is researched, there is nothing to implement” (Werner Nachtigall 2010, p. 198).

3.4 Building Biomimetics

Building biomimetics is a subdiscipline of biomimetics and covers the areas of building design and construction of architecture and civil engineering.

On the basis of core essence of building biomimetics and its methods, building biomimetics is also applicable to industrial design.

Building biomimetics uses biomimetics as tool for creativity.

Building biomimetics connects the classical definition of biomimetics with the analogy researches and with technical biology.

Building biomimetics uses next to the “traditional” methods of “Biology Push” and “Technology Pull,” in particular the method of “Pool Research.”

3.5 Classification of Building Biomimetics

According to the VDI guideline 6220, a product is considered biomimetic when it fulfills these three criteria:

1. Biological precedent
2. Abstraction from biological precedent
3. Transfer and application

The VDI definition implies that all three criteria must be fulfilled. If it is only consistent with one or two of the criteria, then it cannot be described as biomimetic.

In his book *Bionik als Wissenschaft*, which applies the theory of cognition to biomimetics, Werner Nachtigall (2010) signified this process with the subtitle: “Knowledge → Abstraction → Application.”

A definition always becomes difficult in the context of complex products, whose development was shared by several lines of knowledge, among them from the area of biomimetics. On the basis of the dimensions of products from architects and civil engineers and the resulting complex relationships therein, it would be difficult of ascertain a perfect classification according to the precedent of the VDI. There will never be houses completely inspired by biology. Nonetheless, they can be differentiated according to the degree of inspiration, abstraction, and technical application and, furthermore, the significance of biomimetics for the development of a building can be underlined. One can term technical products as biomimetic when the prominent characteristics are biomimetic.

The following *classification for buildings* is to be understood on the basis of an analysis of the development lines and the degree of biological inspiration in the architecture. It facilitates the understanding of building biomimetics. This classification of building biomimetics represents the influence of architectural understanding. For improved understanding of building biomimetics, the following categories are conceived:

Similar to nature: buildings as sculptures similar in appearance to nature
Nature analog: building methods analogous to nature
Integrative: biomimetic principles as components of architecture

3.5.1 Similar to Nature: Buildings as Sculptures Similar in Appearance to Nature

So-called landmarks still play a major role in architecture today, particularly when a building is supposed to be established as a special attraction. Buildings can be used then as built exclamation points, when they set themselves apart from the common perception of the built environment, when they are different from the traditional experience that is taught to us: A house has to be built with angles, with windows, and a pitched roof or, if necessary, a flat roof.

Sculptures that are formed in the “appearance” of nature follow the precedent of Binet (Fig. 3.4) and other realized precedents and are developed as a direct image or as loose interpretation of natural forms. Examples begin with the artistic embellishments for the Casa Milà by Antonio Gaudi and today with the TGV station at Lyon-Satolas by Santiago Calatrava (Fig. 3.5) and Parasol for Sevilla by Jürgen Mayer H. (Fig. 3.6).

Particularly, Santiago Calatrava, the brilliant contemporary Spanish engineer and architect, pushes supporting elements to the limit and stages buildings as sculptures derived from nature, which serve the purposes of function and beauty in equal regard.

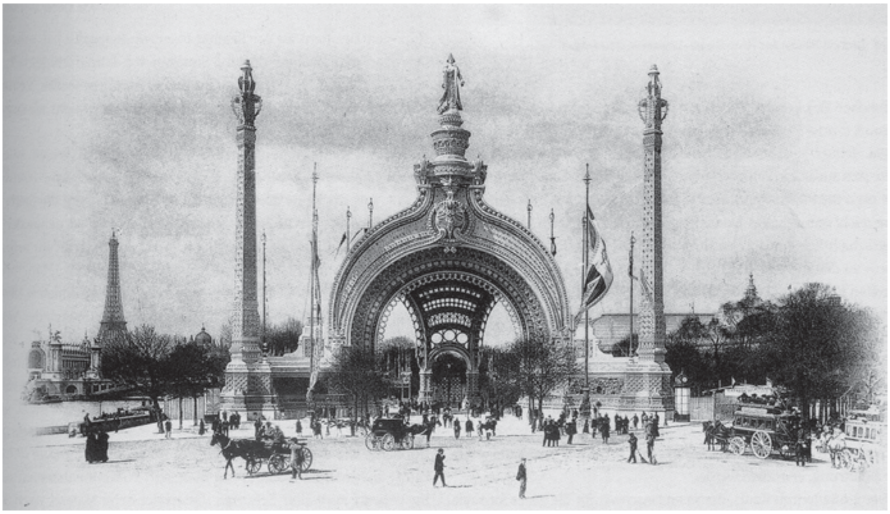


Fig. 3.4 Entrance building for the 1900 World Exhibition in Paris, Georges Binet. (Courtesy of Haeckel House, University of Jena)

Fig. 3.5 TGV station at Lyon-Satolas, architect Santiago Calatrava. (Courtesy of A. de Luz Mendes)

Fig. 3.6 Metropol Parasol, architect Jürgen Mayer H. (Courtesy of K. Köhler)

3.5.2 Nature Analog: Building Methods Analogous to Nature

J.G. Helmcke, biologist, and Frei Otto, architect, discussed in the 1950s and 1960s whether similarities between living and built structures are coincidental or whether conformity to laws also underlies living structures, similar to built structures. From 1970 to 1985, with the collaborative research center (Sonderforschungsbereich, SFB) SFB 64 "Weitgespannte Flächentragwerke" ("Long-Spanning Surface Structures"), studies were conducted under the leadership of Frei Otto on natural structures, which received high international recognition. This research concerned itself, among other things, with networks in nature and technology, expandable structures in living nature and technology, and biology and construction. From 1984 to 1995, it was followed by the collaborative research center SFB 230 "Natürliche Konstructionen" ("Natural Structures"), a research program intended for architecture, urban planning, building structure, and design. With this program, self-forming and self-organization processes in all areas of inorganic and organic nature and technology including house and settlement construction were considered. Self-optimization, form finding, and origination of form in technology and art were likewise researched alongside behavior mechanisms of animals and humans in relation to house and city and the esthetics of natural and technological structures. To the understanding of biomimetics at the time, Frei Otto wrote in SFB 230: "For the streamlining of the topic, biomimetics, or the using of living structures as technological precedent, was not incorporated into the original program. Understanding nature was more important for us than using nature." Obviously this exclusionary

Fig. 3.7 Olympia Stadium in Munich, architects Günther Behnisch and Partner. (Courtesy of G. Pohl)

approach could not be sustained. The study of nature inevitably caused reactions in building form and design. Many architects and engineers have been influenced by the results of the research work from the SFB 64 and SFB 230 to investigate natural structures and gain insights for their creative processes. They discovered the issues of lightweight construction and unlocked the secrets of natural, minimal structures step by step. In the modern pursuit for energy-saving and materially efficient structures, the consideration of findings from research into natural structures becomes more and more essential (Fig. 3.7).

3.5.3 Nature-Integrative: Biomimetic Principles as Components of Architecture

This case involves the integration of biomimetic principles in architectural structures. The integratively termed "structural architecture" helps visualize the real effects of the forces and loads in relation to the used materials.

The relationship with nature will become clear with an example. If one studies the effects of loads on a thigh bone in a cross-section of the bone, he or she will recognize the material reaction to these external conditions in the course of the spongy bone and its density. The internal structural stress leads to a redistribution of the material and to a structurally optimized arrangement of mass. Comparable approaches to structure in architecture have led to developments of minimal surface structures and shell and expanding constructions, for example. In nature the structural system never assumes only one function but fulfills a multitude of various demands simultaneously. Exterior skins perform the tasks of load distribution, substance exchange, and attraction, and occasionally defense against enemies as well (e.g., sea urchin shells).

In architecture, the considerations of complex structural systems of nature can lead to construction of effective and sustainable buildings that would then have to assume a multitude of tasks: structural support, moisture control, acoustics and sound insulation, heat insulation, advantageous forms for internal air flow, advantageous forms for external air flow, volume reduction, material optimization or minimizing, and additionally, the task of design esthetic. A building facade could reach this level of complexity with the use of sophisticated material and functional components, with the use of delicate, low-input structures as well as its physical realization as an updraft facade, combined with storage and cooling masses within the building.

3.6 Potentials of Building Biomimetics

Building biomimetics with its access to the reservoir of ideas and inspirations found in nature can offer the serious potential to better develop technical products.

Observing nature as prototype will not always be crowned with success. However, the failure to consider the potential gain of knowledge from building biomimetics will lead from the start to a reduced palette of possible solutions.

3.6.1 Demands of Modern Buildings: Modern Architecture with the Use of Biomimetic Insights

The demands of modern buildings are, as they have been for the hundreds of years of technological development, characterized by the pursuit for efficient discourse with our resources. It is then to be noted in the current era of computers and the Internet that the diffusion of "new" materials and constructions for ever newer products has been accelerated. The multitude of possibilities has become unimaginable, and this always to the advantage to the task of construction. However, the individual elements of increasingly commonplace technical composite materials are usually inflexibly bound to one another as a complete package. Nature follows a different course in this instance. Its composites decompose after the death of the creature again into its individual parts. But with the aid of computers, technological work methods can resemble the processes of biological genetics sometimes to an astounding degree: Our computer technology enables, for example, "genetic design processes." On a broader front, analogies to biological processes, biomorphic architecture, and biomimetically developed detail solutions, which are being incorporated into building structures, are emerging.

Therefore, it can never be repeated enough that it does not matter in which way the building arrives at its final form, biomimetic or not. The secret of a well-designed building lies in the skillful combination of all creative tools and in the knowledge of technology and praxis.

3.6.1.1 Energy Efficiency, Material Efficiency, and Functionality

The transition from lightweight structures, designated by Frei Otto as "natural structures," to integrative buildings is smooth. The more complex the solution is for the fulfillment of several demands in one structural element, part or building, the more one can speak of "integrative biomimetic principles." The necessity of understanding complex systems often leads to consideration of individual aspects and thereby better explaining the function as a whole.

In nature, material efficiency means the effective discourse with the "expensive" materials produced from metabolic processes. Nature has developed particularly efficient and light shell and fold structures that can grow and be nonetheless stable. Their potential can certainly be fathomed for technological applications. Natural structures have developed building processes in plants and in animals that, on the one hand, negotiate the use of locally accessible raw materials in the form of efficient shell and fold constructions and are structurally optimized and in many regards multifunctional but, on the other hand, can be constructed and expanded with growth processes. Examples are not only the shell structures of mussels and sea urchins, but also the folded structures of leaves: hornbeam, palm varieties, and so on.

After studies of natural growth and optimized forms, the knowledge of bone mineralization and structurally optimized fiber arrangements was abstracted and implemented for the speed skating hall in Erfurt (architects: Julia and Göran Pohl), where they were re-interpreted as pressure-bearing steel struts, so-called bone struts. As components of a combined enclosure and structural system they consist of several spatially linked, arched frames with a superstructure and a substructure. The superstructure is supported with the "bone struts" only at the most structurally necessary positions.

Naturally occurring shell forms served as additional inspirations, such as those of the sea urchin (Fig. 3.8). The strengthening ridges found in the sea urchin shell are represented in the architectural interpretation by individual spanning elements.

Fig. 3.8 Shell structure of the sea urchin *Echinus esculentus* as inspiration for an effective building method. (Courtesy of G. Pohl)

Strictly speaking, the structure of the speed skating hall follows a shell-like beam construction that consists of an arched framework, which exhibits a span-length of 83 m and is radially arranged at the ends. The enclosure as such spans approximately 20,000 m², which can be compared with the area of an entire soccer stadium.

The structure of the "bone struts" was preceded by direct parallel studies on bone and tree growth systems, whose findings were abstracted from the structures of natural systems. The technical interpretation followed on the basis of the performance requirements, namely using simple, industrial fabricated, and commercially available prefabricated products (T profiles) to produce an affordable lightweight structure with the least amount of material waste. This lightweight profile is optimized like its natural "precedent," optimally adapted to its purpose of application (Fig. 3.9).

Comparisons of the sea urchin shell with the shell-like, arched frame structures of the speed skating hall in Erfurt reveal the differences and similarities between the two (Fig. 3.10) .

The ribs can be clearly seen in the image of the sea urchin shell. The similarities between both construction methods arise with spatial merging of the rib structures, which gives the shell construction in both instances its 3D form (although the

Fig. 3.9 Biomimetically developed, so-called bone struts of the speed skating hall in Erfurt, Pohl Architects. (Courtesy of C. Bansini)

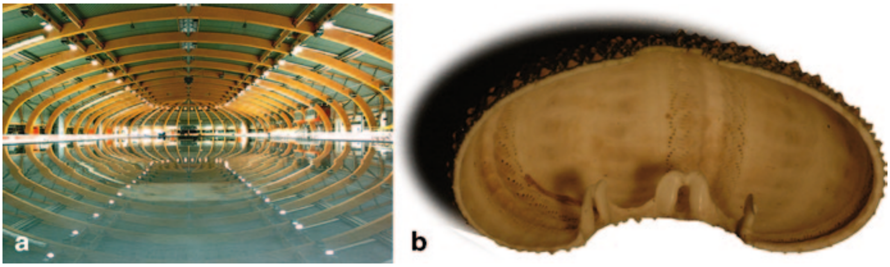


Fig. 3.10 **a** *Left* Interior view of the speed skating hall in Erfurt, Pohl Architects. (Courtesy of G. Pohl) **b** *Right Echinus esculentus*, interior of a shell. (Courtesy of G. Pohl)

individual ribs for the speed skating hall in Erfurt are built as frameworks). The difference is based on the fact that the rib supports the sea urchin shell fused with the shell envelope. In contrast, the structure of the speed skating hall is more skeletal and the shell envelope is not fused with its ribs. The bond is only produced as such so as to distribute external stresses from the envelope to the load-bearing elements, avoiding compression loads (which in theory can also occur within the sea urchin shell, but due to the small dimension of its structure, they would not be able to exert a serious influence on the entirety).

The cited example of the pressure-strut structure for the speed skating hall in Erfurt shows how an optimization and technical application can be reached with the "traditional" material of steel by analysis of natural efficiency strategies. The limitation of the structure consists mostly of the questions of cost-efficient use of prefabricated products to realize an open structure of this type and of materiality and material costs. Neither a massive single strut in the form of a standardized I-beam, nor a solid laminated timber strut instead of the open steel struts would have been capable of yielding the separation of the spatial envelope from the structural system. The expression of the building elements "arch" and "envelope" and with it the comprehension of the structural system is reached by the overcoming of alleged technical constraints—with help of the knowledge of natural optimization mechanisms.

3.6.1.2 Life Cycle

The life cycle plays a commanding role in nature, whether the matured structures are occupied by new life forms or decomposed into its basic elements, from which new life forms can emerge. Researchers are currently developing materials and building elements in the scientific areas of biomimetics that can integrate themselves with a life cycle, as observed in nature. However, research on this subject is only yet at the beginning.

3.6.1.3 Material-Efficient Construction with "Old" and "New" Materials

Often the underlying ideas for the optimization of lightweight structures trace back to the building methods of nature. Natural structures react to internal as well as external influences, and their forms are likewise influenced by such factors, as is the case with technology-based, human-made buildings.

Lightweight materials for envelope structures, which in turn possess good insulation qualities with a high level of light penetration and diffusion, are similar in construction to the system within polar bear fur. The fur of the polar bear fulfills the purposes of insulation and the redirection and even diffusion of light to the dark-pigmented skin below. The hairs are comparable to parallel-oriented glass fibers, which also perform insulation and light distribution simultaneously.

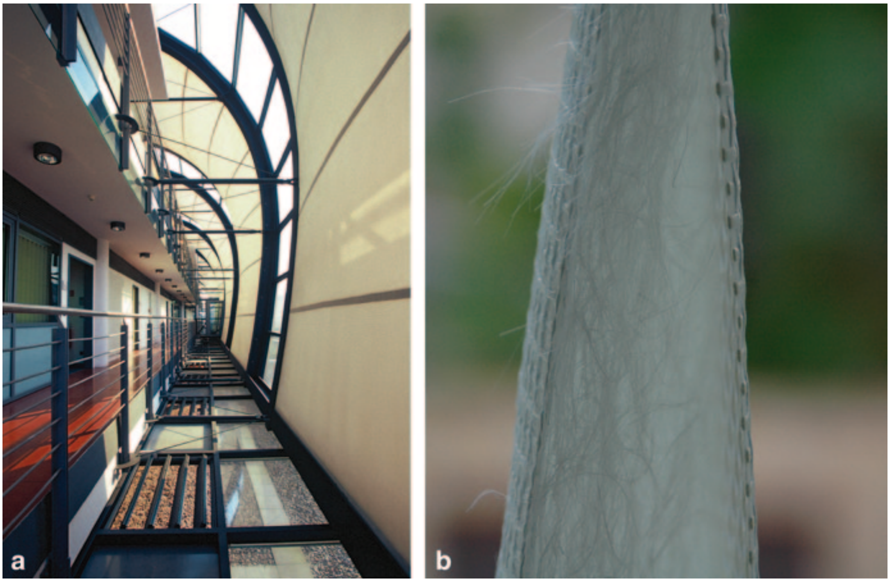


Fig. 3.11 **a** Terminal EF in Erfurt, updraft facade with translucent envelope, Pohl Architects. (Courtesy of G. Pohl) **b** Construction detail of the glass fiber weave for the light diffusion system of Terminal EF, Pohl Architects. (Courtesy of G. Pohl)

The example shown in Fig. 3.11a and b of a facade construction with multi-layered polytetrafluoroethylene glass and interspersed glass fiber weaving fulfills similar functions as the polar bear fur, but adapted to technical demands and without the pigmented underlayer. In contrast to polar bear fur, the weave consists of wool-like, randomly arranged thin glass fibers that scatter the light instead of directing it yet still possess—as with polar bear fur—a heat insulating effect.

This building technique was implemented for a facade structure on the "Terminal EF" building in Erfurt, Germany. It supports the building's cooling system in the summer, conserves warmth in the winter, and provides glare-free work spaces for the entire year. This building skin houses the access and communication areas. The heat insulation value is with 1.1 W/(m²K) comparable to the then (end of the 1990s) conventional glass facades (compare: Sect. 6.37).

3.6.2 Potentials of Nature-Integrating Building Techniques

Nature-integrating systems combine technological knowledge and insights gained from various sources with those that originated on the basis of natural precedents.

3.6.2.1 Biomorphic? A Research Potential for Architects and Engineers

Shell-like and biomorphic structures have once again become popular in contemporary architecture. The form language of architects and engineers, developed with the help of generative methods and computer software technology as non-uniform rational B-splines (NURBS) models, cannot be cost effectively implemented with traditional building technology. Current building systems and technologies can barely keep pace with modern planning tools and can barely fulfill the consequent demands. Examples for a computer-driven fabrication process for timber construction are provided by the Centre Pompidou in Metz by Shigeru Ban (Fig. 3.12).

Higher costs associated with building part production, assembly of auxiliary structures, and the construction itself absorb the otherwise feasible material cost-saving potential and actually exceed than—despite these savings—the normal cost expenditure with traditional building methods. The research effort Bionic Optimized Wood Shells with Sustainability (BOWOOSS) has taken this problem as an opportunity, initiated together with the HTW Saar and the Bauhaus University Weimar, both in Germany. A numerical translation of the results from 3D structures designed for wood fabrication is processed by a computer (CIM) directly on the basis of an optimized result. Wood construction firms, which can work with this kind of 3D data, have already collaborated with specialists for the production technology. The development of new joint and connection details and flexible modules should, as a corollary, be undertaken for suitable materials in order to yield the

Fig. 3.12 Centre Pompidou in Metz, France, under construction, architect Shigeru Ban. (Courtesy of G. Pohl)

desired sustainable results in symbiosis with composite solutions. An optimization approach comparable in its result can be found in nature with shell structures and should be modeled and investigated as a potential for technical derivation.

3.6.2.2 Hierarchical Structures as Optimizing Strategy

The optimizing strategies of the shell constructions in microorganisms had already fascinated Frei Otto and his team at the SFB 230. Analyses of the formation of diatom shells lay at the focus. Presumptions about their functions and a direct implementation in technology were expressly ruled out of the scope of the proceedings. However, new scientific work has indicated clear mechanical constraints for diatoms and additionally the optimization of mechanical features.

Planktontech, a virtual institute of the German Helmholtz Society, concerns itself with the fundamentals and principles of optimization capabilities of lightweight structures in marine microorganisms, in plankton. The shells of diatoms (Fig. 3.13) and radiolarians stand at the focus, which are distinguished by their strength coupled with minimal material application. With the help of modern microscopic observation tools the shells are analyzed, translated into 3D data, and processed with various calculation and optimization tools, making it possible to study the biomechanical characteristics of ocean organisms as well as principles of evolution.

The 3D data are to be used for industrial applications as well, in the area of lightweight building methods. The emphasis lies in the combination of lightweight structures with composite materials for the development of new products in numerous technology sectors such as architecture, automobile design (→ tire rims), and medicinal technology. For this purpose, C. Hamm developed ELiSE (compare Sect. 3.7.2), a tool that searches for structure elements and new forms for technical lightweight structures and makes them available in the form of finite element method (FEM-calculated base forms in a 3D database (Fig. 3.14).

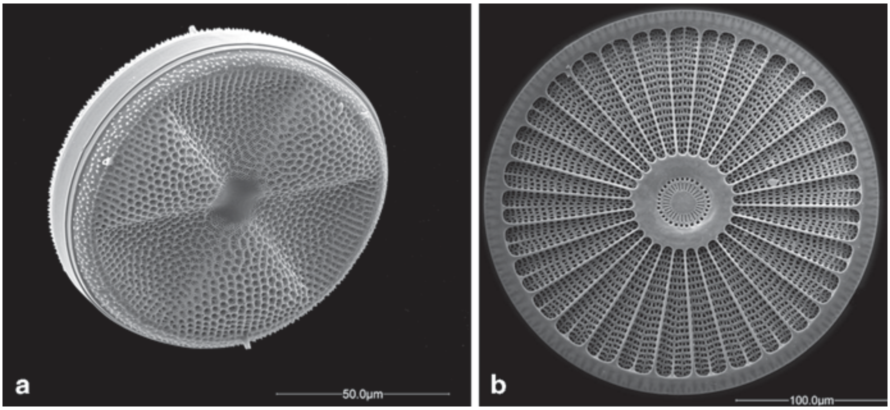


Fig. 3.13 **a**, **b** Diatoms *Actinoptychus* and *Arachnoidiscus*. (Courtesy of Alfred Wegener Institute Bremerhaven)

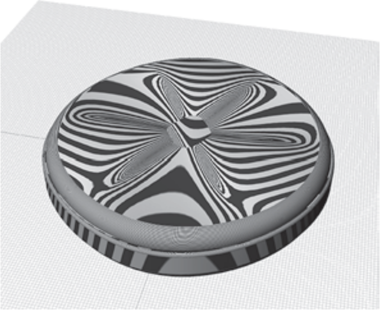


Fig. 3.14 Three-dimensional analysis, representation of the form of *Actinoptychus* for the investigation of various load-bearing stress situations. (Courtesy of Lightweight Structure Institute of Jena)

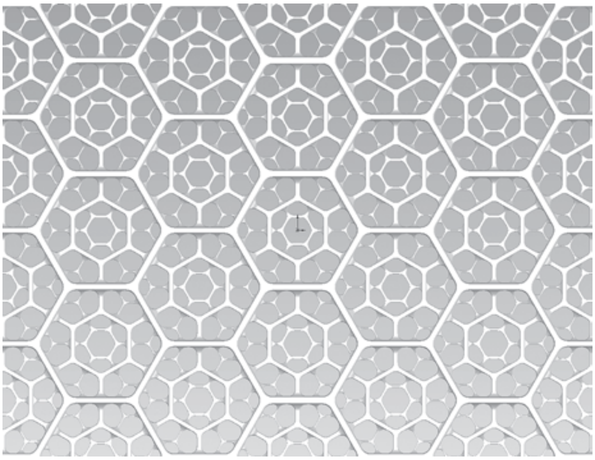


Fig. 3.15 Typical structure of diatom shell, idealized. (Courtesy of Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research)

Members of PlanktonTech include the German Alfred Wegener Institute; Harvard University; Rutgers University; the Universities of Kiel and Freiburg, Germany; the TU Berlin; the Institute for Textile Technology and Process Engineering, Denkendorf; and the Lightweight Structure Institute of Jena, the research department of Pohl Architects.

Measurements of the strength and stability of diatoms, which had been performed in the frame of the research activities of PlanktonTech, have shown that considerable forces must be applied in order to break their biomineralized shells. With the application of FEM calculations on diatom structures, conclusions could be drawn from the material characteristics of the shells. Silicate withstands applications of high tension and pressure and has elasticity similar to the solid bone. In addition, the diatom exhibits an extraordinarily efficient arrangement of structural members inside the silicate shell (Fig. 3.15). The complexity of the shell structure appeared to be important: a simplification of the shell geometry with the same level of material application led to an essentially lower rigidity.

Another task of PlanktonTech is to discover potential areas for application to structures for support and envelope systems of buildings. Normally findings from the areas of biology cannot be directly translated into a technological dimension. The lightweight shells are in this instance certainly exception, as surface pressure and material section can both be scaled in proportion to each other. According to Hamm et al. (2009) a diatom shell can be scaled, for example, by a factor of 10^6 without having to essentially change its internal relative dimensions.

The functions of the shells can also be essentially focused on the factors of mechanical strength and lightweight construction, often in combination with permeability.

It has longer been known that the formation of the diatom shell occurs in special vesicles, the “silica deposition vesicles” (SDV). These vesicles form a hollow chamber inside of which the precipitation of silicate occurs. On the other hand, how the formation of the SDV is driven, is still largely unexplained.

Diatoms attain maximum stability with a minimum of material and therefore follow the same rules as modern lightweight constructions do. This approach is pursued for many different applications in facade and roof structures.

According to the fat droplet hypothesis from Helmcke (compare Sect. 5.1.1), during the process of their shell formation, the diatoms produce fat droplet molecules on the exterior surface whose negative space forms the shell shape with typical openings filled with liquid silicic acid. But this hypothesis, which had at the time been debated in scientific circles, appears completely illogical in light of the well-known multiplicity of forms and the identical formation of a species.

The roof structure of an enclosure for a new train station at Luxembourg-Cessange (Fig. 3.16; prize winner of an international competition for the new construction of the Europa station Luxembourg-Cessange, Pohl Architects with SteinmetzdeMeyer and Knippers Helbig Engineers, compare Sect. 6.26) was designed according to the precedent of diatom shells. The refinement of the structure is hierarchical, starting from a primary structure system to a supporting secondary system and a tertiary structure, which with its triangular grid pattern forms the glass roof. As the basic module, a hexagonal form was chosen that allows from 15.0 to 21.0 m span lengths. The load-bearing structure consists of welded steel tube profiles. The secondary support system is likewise divided into hexagonal modules and spatially forms a dome, so that the roof system supports itself as a shell structure primarily subjected to pressure loads. Upon this structure lies the triangular frame network in 1.50–2.25 m grid that delicately follows the dome forms of the secondary structure and carries the glazing.

As approaches to the application of hierarchical structures, as they occur with radiolaria, a series of tests were performed in the frame of the collaboration with the research institute Planktontech at the ITV Denkendorf for carbon-fiber-reinforced polymer hexagon structures to help better understand the hierarchical silicate constructions of diatom shells and to generate test structures for facades and roof elements. The sheathing of a water tower in Chemnitz, Germany, is planned as an

Fig. 3.16 Train station roof at Luxembourg-Cessange, Pohl Architects with SteinmetzdeMeyer and Knippers Helbig Engineers. (Courtesy of rendertaxi/Pohl Architects)

application for a hierarchical facade construction (Fig. 3.17a and b, design: Pohl Architects).

The multiaxial, transformable roof for the open-air theater in Feuchtwangen, Germany (design: Julia and Göran Pohl, Fig. 3.18) stands as a glass-fiber-reinforced plastic (GFRP) structure in its test phase. For the lamella-like GFRP wings that are 18.0 m long and 2.6 m wide, subsupport frames of glass fibers are integrated in triangular recesses. The hierarchical structuring is in this case also a further development of the shell principles of diatoms and uses the design approach of using standardized industrial building elements for the advantage of simple assembly.

The shape of the columns for the roof structure (Fig. 6.52, Sect. 6.52) visualizes the features of optimizations, which had already been implemented in an analogous approach with the speed skating hall in Erfurt. The branches are used similar to tree limbs. Welded steel tube profiles are once again used, which corresponds to the location of structural stress.

3.6.3 Evolving Design and Evolutionary Urban Planning

The possibilities of modern computer technology lead to selection processes that can be to a certain degree similar to those of natural evolution. At the Institute for Computer-Based Design, ICD, at the University of Stuttgart, Germany, Achim Menges and his colleagues have researched the possibilities of computer-supported

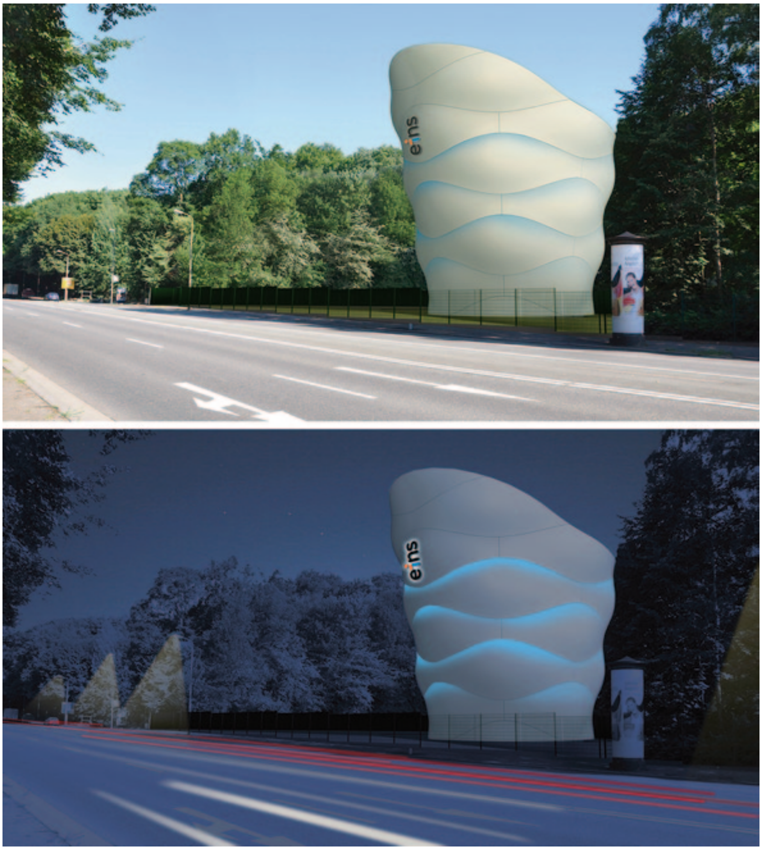


Fig. 3.17 **a**, **b** Studies for the sheathing of a water tower in Chemnitz, Germany, with hierarchical facade elements with a fiber composite, lightweight method of construction. Pohl Architects. (Courtesy of N. Feth)

algorithms for evolutionary design strategies (Sect. 6.23) and evolutionary urban planning (Sect. 6.27). In cooperation with the Institute of Building Structures and Structural Design, ITKE, at the University of Stuttgart, led by Jan Knippers, building structures are studied and optimized for their engineering–technical function, their structural behavior, and—in special cases—their mobility. From this collaboration, fascinating biomimetic-inspired buildings and structures are developed.

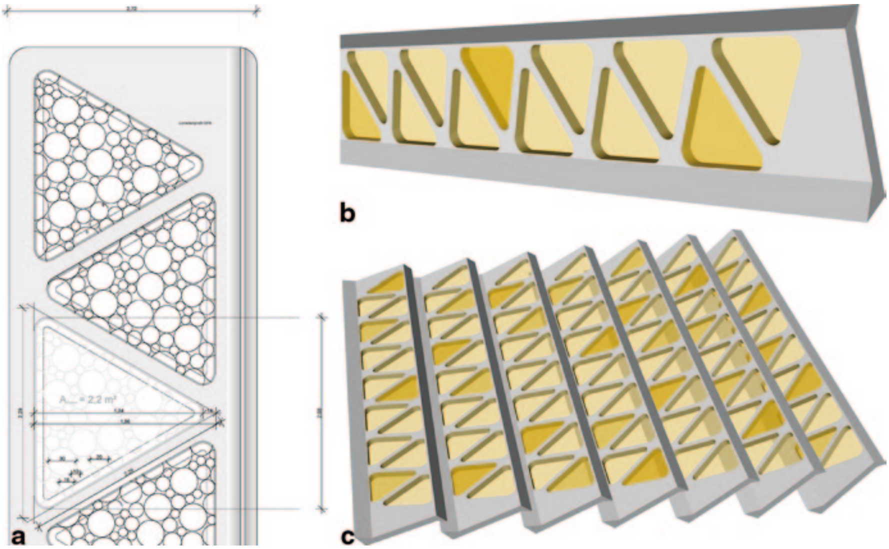


Fig. 3.18 Roof structure of the open-air theater in Feuchtwangen, Germany. Pohl Architects. **a** Hierarchical subdivision of the frame structure with porelike, celled elements. **b** The elements show a design variation with differently colored glass panels that were discarded in the final planning phases, as the colors would have interfered with the stage scene. (Courtesy of Pohl Architects)

3.7 Methods and Approaches Related to Building Biomimetics

Building biomimetics applies to architects and civil engineers. The predominant methods used by these fields have been discussed in the preceding sections. Alongside these methods further tools and approaches exist that follow similar paths and should not remain unmentioned in this context.

3.7.1 Scionic®: Industrial Design and Biomimetics

At the University for Arts and Industrial Design in Linz, Austria, a connection between inductive inspiration and industrial design and serial production is taught under the leadership of Axel Thallemer. According to Thallemer, Scionic® focuses “on heuristic inspirations from nature, virtual model building, and iterative optimization, as well as empirical verification of the found forms. In (natural) scientific base research,” and formed products “in interaction with esthetic, technological, scientific, and psychological factors.”

The theoretical superstructure was specified in Thallemer and Reese (2010) “Visual Permutations” and Thallemer (2010) “Scionic.”

The education program for industrial design at the University for Arts and Industrial Design in Linz describes Scionic® as synergy between the factors described by Thallemer. “As a distinction from the perception of the now loaded term ‘design,’ the neologism of Scionic® is propagated for the same purpose. This term references the fundamental knowledge database of nature as a sign in the sense of syntax, semantics, and semiotics.” Products can emerge as such, whether they are of virtual or real nature, mobile, or immobile.

3.7.2 Methods of Structure Optimization and Self-Organization

At the Karlsruhe Institute of Technology, KIT, Claus Mattheck developed particular methods with the goal of structure optimization according to precedents from biology. At KIT, the Institute for Material Research investigates strategies of nature for the structural optimization and the potential of these insights for the application in technology.

Nature does not principally optimize all of its building processes. On the basis of access to nutrients, energy, and building materials, structures have been developed that either demonstrate little optimization or are exceptionally thrifty in their use of locally accessible resources. These processes use the so-called Soft Kill Option (SKO) method. This method simulates the mineralization in a bone, where high-stressed areas are structurally strengthened and less-stressed ones reduced in mass. Applied to technical structures, the SKO strategy leads to efficient use of materials and therefore a lightweight structure (Fig. 3.14). The SKO method is effective for support structures and defines the directions of stress within the structures so that areas under more stress are supplied with more strengthening material and non-structural areas receive less material mass. According to this principle, very efficient and lightweight construction methods can be developed, predominantly with application in machine and vehicular design.

Another and, in principle, simple and therefore diversely applicable method is Mattheck’s “Method of Tension Triangles.” This method is a graphic tool for the production of contours along directions of forces. The method of the “tension triangles” is a graphic method for the rounding of transitions with a forking or bending of the material. It describes, with help of simple geometric definitions, branches in the structure that are superior to the perpendicular geometries in common structures. The model contour retained as such is used for areas dominated by shear forces, for example, notches and sectional transitions, to induce mechanically efficient flows of forces. If the form of the component deviates from this flow of forces, the notch stress can be reduced by a local augmentation of the “form contour.” Otherwise weight and material can be saved by a diminishment of the form (“shrinking”) if there is unnecessarily high material mass (Fig. 3.19).

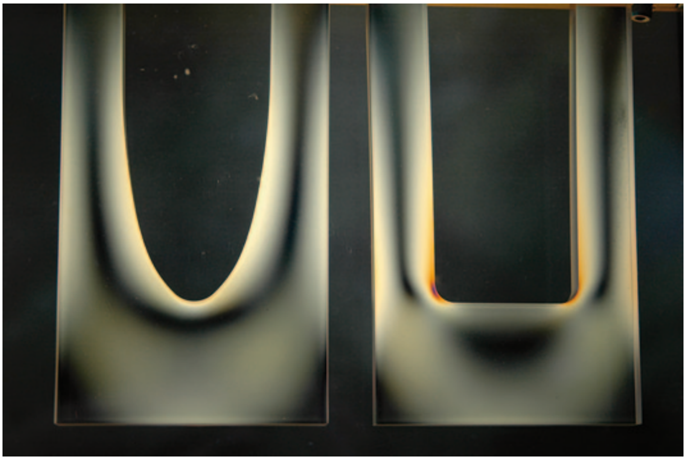


Fig. 3.19 Visualization of the behavior of forces in transition zones from a thick to thin cross-section of two steel components: **a** A tension-optimized construction developed according to the "Method of the Tension Triangles." **b** A traditional design with straight edges and rounded corners, model: KIT. (Courtesy of G. Pohl)

A closer description of the SKO method and its application is found in Sect. 6.21. Section 6.22 subsequently introduces the method developed by Frank Mirtsch for self-organization, a process of producing strength-enhanced sheet metal using indentations.