BS ISO 18458:2015

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Biomimetics — Terminology, concepts and methodology

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National foreword

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The UK participation in its preparation was entrusted to Technical Committee AMT/-/4, Biomimetics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2015

ISBN 978 0 580 81320 7

ICS 07.080

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 May 2015.

Amendments/corrigenda issued since publication

Date	Text affected

INTERNATIONAL STANDARD

ISO 18458

First edition
2015-05-15

Biomimetics — Terminology, concepts and methodology

Biomimétique — Terminologie, concepts et méthodologie

Reference number
ISO 18458:2015(E)

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Foreword

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The committee responsible for this document is ISO/TC 266, *Biomimetics*.

Introduction

Biomimetics is understood to be the application of research and development approaches of interest to practical applications and which use knowledge gained from the analysis of biological systems to find solutions to problems, create new inventions and innovations, and transfer this knowledge to technical systems. The idea of transferring biological principles to technology is the central element of biomimetics (see Clause 3 for a definition of biomimetics).

The basic motivation behind the transfer of biological solutions to technical applications is the assumption that biological structures are optimized to their needs and can be the source of significant and convincing applications. To date, over 2,5 million different species have been identified and described to a great extent together with their specific characteristics. In terms of biomimetics, there is therefore a gigantic pool of ideas available for solutions to practical problems.

Historically, the development of biomimetics can be divided into the following phases:[1] model-based biomimetics was introduced starting around 1950 primarily for use in the design and construction of aircraft, vehicles, and ships by deriving modelling rules based on similarity theory for transferring the principles of biological systems to technical designs. Around 1960, the two pillars of biomimetics (biology and technology) were combined linguistically for the first time due to the influence of cybernetics and placed on a common linguistic and methodical foundation. This foundation then became an important basis for the central element of the field of biomimetics: the transfer of knowledge. Since about 1980, biomimetics has also been extended down to the microscale and nanoscale (e.g. the Lotus-EffectText ®) [2]. New methods in measurement and manufacturing technology were the keys to these extensions. Since the 1990s, biomimetics has received further impetus, in particular due to the rapid technological development in the related fields of computer science, nanotechnology, mechatronics, and biotechnology. In many cases, it is new developments in these fields that enable the transfer of complex biological systems in the first place[3].

Today, the field of biomimetics is increasingly considered a scientific discipline that has generated numerous innovations in products and technologies. This highly interdisciplinary collaborative work, which brings together experts from the fields of biology, engineering sciences, and numerous other disciplines, possesses a particularly high potential for innovation[4]. For this reason, biomimetics has now become an object of research and education at numerous universities and extramural research institutions. However, manufacturing companies are also increasingly turning to biomimetic methods to develop new products or to optimize existing products. In spite of the increasing number of researchers and users active in the field of biomimetics, the transfer of knowledge from the field of biology to technology is still a complex process that places high demands on the people involved.

Nature has numerous “ingenious solutions” available that can often be understood intuitively. It is seldom easy, though, to explain the underlying mechanisms and in particular, to explain how they could be applied to technology. This discrepancy is one reason for the current and ongoing relevance of the field of biomimetics, which will also continue into the next decades[5].

Biomimetics — Terminology, concepts and methodology

1 Scope

This International Standard provides a framework for the terminology on biomimetics in scientific, industrial, and educational purposes.

This International Standard is intended to provide a suitable framework for biomimetic applications. The field of biomimetics is classified and defined, numerous terms are described, and a description of the process of applying biomimetic methods from the development of new ideas to the biomimetic product is provided. The limits and potential of biomimetics as an innovation approach or as a sustainability strategy are also illustrated. In addition, this International Standard provides an overview of the various areas of application and describes how biomimetic methods differ from classic forms of research and development. If a technical system is subjected to a development process according to this International Standard, then it is allowed to be referred to as a "biomimetic" system.

This International Standard provides guidance and support for developers, designers, and users who want to learn about the biomimetic development process and integrate biomimetic methods into their work aiming at a common language for scientists and engineers working in the field of biomimetics. It can be applied wherever nature has produced a biological system sufficiently similar to the technical target system that can be used to develop a technical equivalent.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
abstraction
inductive process in which a general conclusion is drawn based on the observation of a specific object

Note 1 to entry: In biomimetics, this conclusion is ideally a physical context for describing the underlying functional and operating principles of the biological systems.

2.2
analogy
analogy in terms of technology is understood to be a similarity in the relationships between the relevant parameters used to describe two different systems

Note 1 to entry: The specification of the relevant parameters is the object of *abstraction* (2.1). In terms of its definition in the field of *biomimetics* (2.9), one of these two systems is a *biological system* (2.6), and the other system is the technical target system.

Note 2 to entry: In biology, the term "analogy" refers to similarities in functional characteristics between different organisms that resulted from the need to adapt and not because the organisms are somehow related. In contrast, similarities based on relationship dependencies, and therefore on similar genetic information, are referred to as homologies. In biology, the term "analogy" has come to be understood dynamically and emphasizes in particular the differences between the starting points of two evolutionary developments.

2.3
analysis
systematic examination in which the biological or technical system is decomposed into its component parts using suitable methods, after which the parts are then organized and evaluated

Note 1 to entry: The opposite of analysis, in terms of its aspect of "resolution into individual parts", is referred to as synthesis (recomposition).

2.4
bioengineering
application of engineering knowledge to the fields of medicine or biology

2.5
bioinspiration
creative approach based on the observation of *biological systems* (2.6)

Note 1 to entry: The relation to the *biological system* (2.6) may only be loose.

2.6
biological system
coherent group of observable elements originating from the living world spanning from nanoscale to macroscale

2.7
biology push
biomimetic development process in which the knowledge gained from basic research in the field of biology is used as the starting point and is applied to the development of new technical products

Note 1 to entry: In technology, biology push is considered as a bottom-up process.

Note 2 to entry: In design research, biology push is considered as "solution driven"[6].

Note 3 to entry: See also *technology pull* (2.19).

2.8
biomimicry
biomimetism
philosophy and interdisciplinary design approaches taking nature as a *model* (2.15) to meet the challenges of *sustainable development* (2.17) (social, environmental, and economic)

2.9
biomimetics
interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of *biological systems* (2.6), their *abstraction* (2.1) into *models* (2.15), and the transfer into and application of these models to the solution

Note 1 to entry: Criteria 1 to 3 of Table 1 shall be fulfilled for a product to be biomimetic.

2.10
bionics
technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents

2.11
component
element of an assembly that cannot be decomposed any further

2.12
function
role played by the behaviour of a *system* (2.18) in an environment

2.13
invention
act of creating something new or improved or product of this creation

Note 1 to entry: An invention therefore differs from an innovation, for which market diffusion is a prerequisite.

2.14
material
collective term for the substances needed to manufacture and operate machines, but also to build constructions

Note 1 to entry: The term “material” is used in the following as a general term for all biological materials and structures.

Note 2 to entry: It includes raw materials, *working materials* (2.20), semi-finished products, auxiliary supplies, operating materials, as well as parts and assemblies. The term “material” is used in the sense of *working materials* (2.20).

Note 3 to entry: Biological materials are organic and/or mineral substances produced by living organisms. Due to their hierarchical structure from the molecular to the macroscopic level, it is not possible to clearly distinguish between the terms “material” and “structure” in the field of biology.

2.15
model
coherent and usable *abstraction* (2.1) originating from observations of *biological systems* (2.6)

2.16
structure
type and arrangement of the *components* (2.11) in a *system* (2.18)

2.17
sustainability
sustainable development
development that satisfies the requirements of the present without risking that future generations will not be able to satisfy their own requirements

Note 1 to entry: Nature technology is the concept of human and the earth conscious technology learning from the perfect circulation of the nature that has super-low environmental burden, high functionality, and sustainability[7].

2.18
system
set of interacting or interdependent *components* (2.11) forming an integrated whole with a defined boundary

2.19
technology pull
biomimetic development process in which an existing functional technical product is provided with new or improved functions through the transfer and application of biological principles

Note 1 to entry: Technology pull is considered as a top-down process.

Note 2 to entry: In design research technology, pull is considered as “problem driven”[6].

Note 3 to entry: See also *biology push* (2.7).

2.20
working material
prepared raw material in a formed or unformed state (solid, liquid, or gaseous state) that is used to manufacture components, semi-finished products, auxiliary supplies, or operating materials

3 What is biomimetics?

3.1 Essentials of biomimetics

The successful application of biomimetics is characterized as the transfer of knowledge and ideas from biology to technology or other fields of innovation, i.e. practical development inspired by nature that usually passes through several steps of abstraction and modification after the biological starting point. The field of biomimetics is highly interdisciplinary and multidisciplinary, which is indicated by the high level of cooperation between experts from different fields of research, for example, between biologists, chemists, physicists, engineers, and social scientists.

Depending on the intensity with which biomimetics is applied, it can be understood as a scientific discipline, an innovation process, or a creativity technique. In innovation management, biomimetics is used as one of many creativity techniques. However, its potential is not fully realized when viewed solely as a creativity technique because the development of new ideas in this case often remains at the level of a search for obvious analogies between biological systems and technical problems without performing a systematic analysis, abstracting, or transferring an operating principle.

The innovation process in biomimetics starts by linking a biological system to a specific technical question. The characteristic feature of biomimetics is that it unites interest in knowledge from the field of biology with the goal of obtaining a real technical implementation.

In biomimetics, the conceptual interest in and research on the biological system is oriented to obtaining applications. Structure/function relationships are particularly important in this context. These relationships are derived primarily from the analysis of the functional morphology in the framework of organismic biology. An essential part of a successful biomimetic process is the design of the interface between biological research and product and process development engineering. Biomimetics is not only about transferring abstracted biological results to technology, but also about applying the engineering methodology to biological systems and integrating knowledge of biological systems into technical developments. An efficient and multi-layered transfer of knowledge, and especially of methods, between the disciplines therefore forms the basis for a successful biomimetic development process.

Biomimetics is founded on basic research in the field of biology. Due to its defined focus on applications, though, it primarily integrates application-oriented and applied research into the actual development of the product or process.

Since it is inherently a type of innovation process, biomimetics is currently becoming a separate scientific discipline. On the one hand, it is steadily developing a system of interrelated scientific statements, theories, and methods, while on the other hand, associations, research and educational institutions, as well as communication tools, are being established by certain groups of people under the banner of biomimetics.

3.2 Boundaries to and areas of overlap with related sciences

The expression “technical biology” was introduced by *Werner Nachtigall* to distinguish it from biomimetics[8]. Technical biology consists of the analysis of structure/function relationships between biological objects with help of methodical approaches taken from physics and the engineering sciences. Technical biology is therefore the starting point of many research projects in biomimetics because it allows a deeper understanding of the method of operation of the biological system at the quantitative level, as well as a suitable implementation in technical applications.

Over the last few years, it has become apparent that knowledge gained through the implementation of biologically inspired principles of operation in innovative biomimetic products and technologies can contribute to a better understanding of the biological systems. This relatively recently discovered transfer process from biomimetics to biology can be referred to as “reverse biomimetics”. In contrast to technical biology, reverse biomimetics does not apply classical engineering methods and analysis tools to biological systems, but uses biomimetic prototypes as a whole and/or the simulation of their method of operation as explanatory models or models for study with which it can be easier to understand the underlying biology. In an iterative process, the methods of technical biology are then applied again in the next step in order to test this new or extended explanatory model on the biological system. The new knowledge of the biological structures and functions gained then flows back into the development of improved biomimetic products and technologies, which then in turn serve as improved biomimetic models to which reverse biomimetics can be applied, etc. This results in new knowledge in the form of a heuristic spiral of technical biology, biomimetics, and reverse biomimetics[9].

The boundary separating biomimetics and biotechnology is also important. Both fields are areas of applied biological research (translational biology). Biotechnology is understood to be the application of scientific and technical principles to convert substances using biological agents with the goal of providing goods and services (based on Reference [10]). In contrast, biomimetics uses living organisms as generators of ideas for innovative technical implementations, but the organisms themselves are not necessarily involved in the manufacturing of biomimetic products. Even though the concepts of biotechnology and biomimetics are not the same, they can be combined, as has been demonstrated by research projects on the development of artificial spider silk, for example, see Reference [11] (see Table 1 and A.2).

Biomimetics is a highly interdisciplinary science possessing numerous facets. In fact, there are also publications containing biomimetics terminology in the economic sciences and in organization management that, based on the analysis of biological systems, provide suggestions for improvement to existing concepts and strategies[12][13][14]. However, it is not always easy to recognize the aspect of technology in these fields as it is used in the definition of biomimetics or it might be necessary to expand the definition of the term "technology" to recognize it.

In contrast, areas of research that deal only with inanimate elements of nature (geo-inspired) are incompatible with the definition of biomimetics provided above. This includes, for example, research on snow crystals, which can provide valuable information for the production of nanostructures like those needed for microchips[15] or for the development of sound-absorbing materials.

The use of shapes designed based on biological systems alone cannot be considered a biomimetic approach, particularly when the shapes appear from the outside as if they could be based on a shape found in nature but are really based on sophisticated CAD technology or other mathematical methods for designing surfaces, for example. In these cases, biomimetics only plays a role when the design of the shape is an integral part of the functionality developed according to biomimetic principles.

3.3 Biomimetic products and processes

The decision as to whether a product or technology can be considered biomimetic can be made based on three criteria (steps) (see Table 1).

A product can be considered biomimetic if, and only if, it follows the following three steps defining the biomimetic process:

— function analysis has been made of an available biological system;

— biological system has been abstracted into a model;

— model has been transferred and applied to design the product.

Parallel developments in nature and technology are not biomimetics. In the course of the development of technology, many technical products were developed and in many cases without any knowledge of natural phenomena that were amazingly similar to biological structures with comparable tasks in terms of their function and sometimes even in terms of their shape.

Table 1 — Differentiating between biomimetic and non-biomimetic products based on Reference [16]

	How new ideas are developed	Criteria for a biomimetic product			CONCLUSION: Biomimetics yes or no[a]
		1. Function analysis of biological system	2. Abstraction from system to model	3. Transfer and application without using the biological system	
CAO method (see A.1)	technology pull	+	+	+	yes
Biomimetic spider silk (see A.2)	biology push				
Process step1: Molecular biomimetics		+	+	+	yes
[a] Criteria 1 to 3 shall be fulfilled before "yes" is entered as the conclusion.					

Table 1 *(continued)*

	How new ideas are developed	Criteria for a biomimetic product			CONCLUSION: Biomimetics yes or no[a]
		1. Function analysis of biological system	2. Abstraction from system to model	3. Transfer and application without using the biological system	
Process step 2: Recombinant protein production		-	-	-	no
Process step 3: Material processing		+	+	+	yes
Evolutionary algorithms (EA) for optimization (see A.3)	technology pull	+	+	+	yes
Fin ray structure (see A. 4)	biology push	+	+	+	yes
Lotus-Effect® (see A.5)	biology push	+	+	+	yes
Self-sharpening cutting tools (see A.6)	technology pull	+	+	+	yes
Art Nouveau (see A.7)		+/–	+/–	–	no
Fibonacci sequence (see A.8)		+/–	+/–	–	no
Olympia roof in Munich (see A.9)	independent development	–	–	–	no
Reinforced concrete (see A.10)		+	–	+/–	no
Result of optimization with EA (see A.3)		+	–	–	no
Soap film analogies (see A.11)	independent development	–	–	–	no

[a] Criteria 1 to 3 shall be fulfilled before "yes" is entered as the conclusion.

4 Reasons and occasions for using biomimetic methods

4.1 Possibilities, performance, and success factors for biomimetics

In the search for innovative solutions, biomimetics acts as a supplement to the classic methods for developing new ideas and is a way of approaching scientific engineering work methods (see Reference [17], Chapter 2). The diversity of biological solutions is particularly interesting for biomimetic developments. Today, millions of species inhabit every type of environment and their amazing adaptations offer a virtually infinite number of potentially relevant solutions from a technology point of view[18].

A general reason for the ability to transfer a biological property to a technical system is the fact that the same physical laws and constants are valid in biology and in technology. The study of plants and animals sometimes leads to problem solutions that are amazingly similar at first glance to the corresponding technical solutions, but when subjected to more detailed analysis, often exhibit significant differences (see Reference [19], p 477-478). Characteristics of biological structures include multi-criteria optimizations with sometimes contradictory functions (multifunctionality) while simultaneously providing a high level of operational reliability, the ability to adapt to variable environmental conditions (adaptivity), a high level of error and failure tolerance (resilience and redundancy), and the ability to self-organize. The systematic transfer of these and other autonomous functions of biological systems such as self-repair, self-regeneration, and self-assembly, for example, can be a huge benefit when developing increasingly complex products[20].

4.2 Biomimetics and sustainability

The specification of reasonable strategies for sustainable technical development is still impossible in spite of the availability of numerous tools for evaluating technology, due in particular to the level of system complexity and uncertainty in parameter values. In light of these facts, an innovation approach that by definition at least increases the probability of a "more sustainable" technology would be immensely important. The question is whether or not biomimetics is an example of such an innovation approach.

In nature, species in an ecosystem are in constant interaction and dynamic homoeostasis. Metabolic processes, behaviours, sizes of territory, and specializations mutually adjust to each other.

Furthermore, nature also shows us how solar management, opportunism (use of what is available), resource efficiency, recycling management, cascade utilization, and self-organization can generate complex modular structures and multifunctionality when subject to mild environmental conditions[20]. Since biological systems are also based on adaptivity, redundancy, diversity, barriers, and, in many cases, self-healing capabilities at the macroscopic, as well as at the microscopic scale, they possess an inherent fault tolerance. This prevents large-scale secondary damage as a result of minor errors or disruptions.

Due to these numerous discoveries, many scientists believe that hopes for a more ecological technology through the application of biological systems/models and principles to technology are at least partially justified[22].

The desired tendency to move towards making a positive contribution to sustainability shall not lead to a sweeping, positive assessment of biomimetics. When transferring biological solutions to technology, the material basis is generally adapted to the technical requirements and capabilities. Furthermore, the adaptation to the environment when transferred to a new context is rarely as good as in the case of the natural organism used as the model. For this reason, it is now undisputed that such statements cannot be generalized and that any statements regarding the quality of a biomimetic solution can only be confirmed or denied by examining in detail each case individually[1][22][23].

The contribution of biomimetics to the sustainability goal of "maintaining biodiversity" also needs to be emphasized. On the one hand, biomimetic innovations generally demonstrate the economic importance of biodiversity, which should also be available to future generations as a source of options[24][25]. On the other hand, the cultural function of biodiversity and nature (in the sense of a teaching nature) and the respectful handling of these values are increased through biomimetic projects.

Another opportunity is opened by biomimetics due to its inherent property of bringing together people from traditionally separate fields in science and technology that previously had little contact with each other. This creates new forms of interdisciplinary and transdisciplinary cooperation and generates cross-discipline methods and tools for efficient innovation processes. This could become an important basis for the management of complex systems, which almost all of the systems arising in the context of sustainable development are.

Basically, it can be expected that biomimetics, when its use becomes widespread, will lead to a diffusion and utilization of the knowledge of biological efficiency and consistency strategies by technical and scientific people not traditionally involved in biological disciplines. For this reason, the hope that technology will reflect nature more and more over the long term in the sense of a "softer" technology created by an innovation approach based on biomimetics is justified.

Correspondingly, biomimetics at least offers the potential for a more sustainable innovation approach. The extent to which the hopes derived from this potential are justified also depends, in this case, on the willingness of the people involved to be guided by the vision of sustainable development.

4.3 Limits of biomimetics

A detailed analysis of biomimetic processes and work methods is only possible when the complete process, from the biological system to the innovative technical product and process, are examined (see Reference [26], Chapter 12). In addition, the possibilities and the limits of biomimetics shall be presented clearly[8].

— Biomimetics is a supplement, not a replacement. Traditional design processes used by engineers will also form the foundation in the future for new technical developments and refinements. Proven and established engineering procedures should not necessarily be replaced by biomimetic procedures. Instead, biomimetics should serve as an additional development tool.

— Biological systems often solve many concurrent challenges with unique structures. This gives rise to highly complex structures that can be very challenging to understand and apply to simpler technical problems (see Reference [26], Chapter 10).

— Scalability – moving from micro to macro scale exposes design to new constraints. Some biological mechanisms work at the nano scale but fail to work on the macro scale.

4.4 Communication process in biomimetics

The interdisciplinarity needed in the biomimetic development process results in special challenges to the communication process. Biologists and engineers communicate using their own distinct terminology and language. For this reason, explanations are necessary that both will be able to understand. In general, though, it is not easy to replace all special terms with terms used in daily life. The reason for this is the fact that terminology not only plays a communicative role for experts, but is also the foundation of their categorical perception[27]. Experts shall first “decode” their knowledge before they can communicate it.

Terms often have different meanings in different scientific disciplines. For example, the term “formal” in architecture and design is understood in the sense of “related to the form”. In many other scientific and technical fields, though, a formal action is understood to be an action that strictly follows a prescribed rule. The same can be said for the term “fiber”, for example, which in biology refers to a group of elongated cells or threadlike structures in an organism, which in materials science it refers to a thread-like filament used to make a material[28].

The examples point out the necessity to be more aware of the terminology used. It is necessary to question the definitions of apparently well-understood terms. The need to question these definitions increases the more frequently a term is used in the particular scientific discipline. The more sure you are of the meaning of an established term, the less its meaning will be questioned and the smaller the danger of creating misunderstandings.

If these challenges are overcome, then interdisciplinary communication will become the basis of the biomimetic development process and allows for a fast and in-depth understanding of the various fields.

5 Biomimetic engineering process

5.1 General

A deeper understanding of the work methods used in biomimetics is a prerequisite for recognizing the full potential of biomimetics for the development of technical innovations, but also to avoid generating inappropriate expectations on biomimetics and to explain the sometimes relatively long development cycles in biomimetic projects. Due to the interdisciplinary work involved in biomimetic research and development projects, the efficient transfer of the results of this research to technical products along the entire value chain is only possible through close cooperation among biologists, engineers, and experts from other disciplines.

The typical methodology used in biomimetics is shown in Figure 1. The linear and sequential structure depicted represents an ideal case that has the potential of being integrated into the entire value chain. In reality, it will be necessary in many cases to carry out some steps recursively and in parallel.

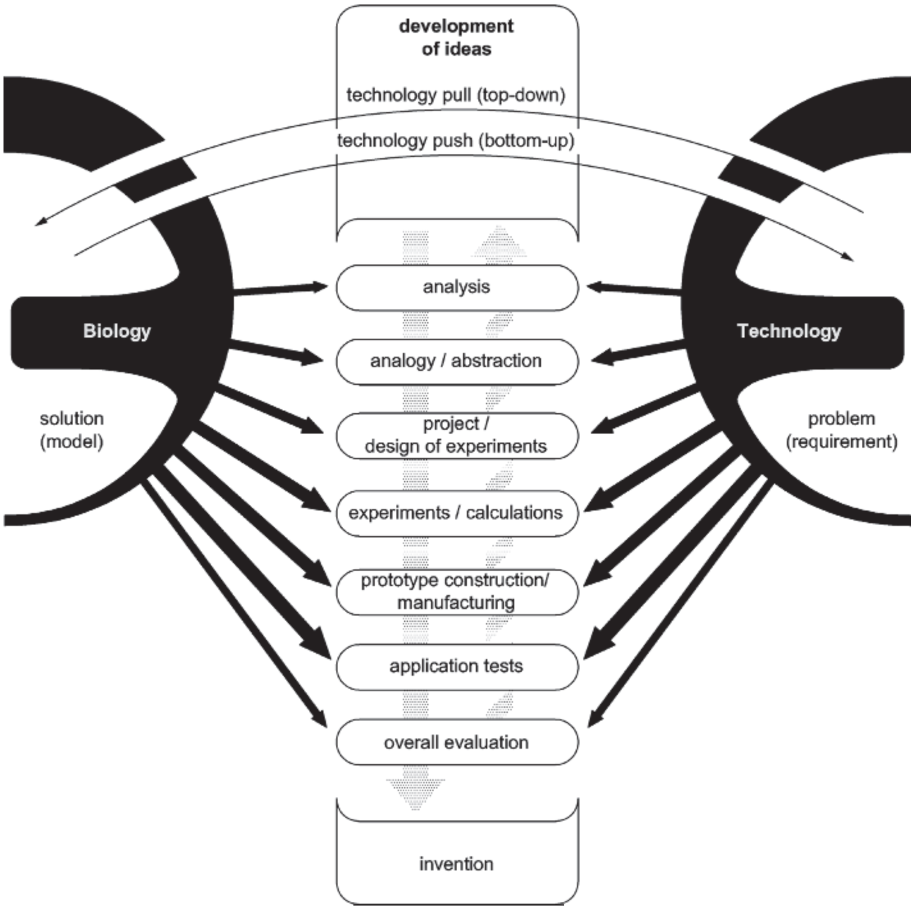


Figure 1 — Simplified flow chart of a biomimetic development process[29]

The development of new ideas is a prerequisite for application-oriented research. After a new idea is developed, the biological system is analysed and abstracted. A function analysis is performed and suitable experiments or system-based analyses of the technical objectives are designed and executed. Based on the results, possible explanations are formulated in the abstraction phase. Initial ideas for the design and manufacturing of the technical process or product are usually generated during the development of new ideas, during the analysis phase, and during the abstraction phase.

The actual development work is performed in the third phase. The particular sequence of steps taken when carrying out this development work differs from scientific discipline to scientific discipline and it is therefore impossible to specify a generally applicable methodology. The result of the biomimetic process is an invention in the form of a new solution.

Only after successful introduction to the market does the invention of a biomimetic product or process become an innovation. In addition to excellent basic and application-oriented scientific research, studies specifically for the purpose of describing, specifying, and standardizing biomimetic procedures for the development of a catalogue of "good practices" are becoming increasingly important for the long-term and successful establishment of biomimetics as an innovation approach in industry.

5.2 Development of new ideas

The development of new ideas is the main step on the path to an invention. The development of new ideas is influenced by (previous) knowledge, flexible processing of knowledge and information, and motivation. In biomimetics, the creative starting point is reached when a technical problem is linked to a solution suggested by biology. It is very difficult to determine the quality of an idea in terms of its originality, usefulness, and feasibility. The interdisciplinary character of biomimetics, though, provides a favourable starting point because the people involved have inherently different approaches and strategies for a solution due to their correspondingly specialized knowledge and skills.

The starting point for the development of new ideas can come from biology (biology push) or from the engineering sciences (technology pull). Furthermore, a complete picture also needs to include the customers and the market as additional parties, and these parties can also be the goal or the starting point of development (see Reference [17], pages 152 to 156) In this context in classic innovation theory, this is referred to as a technology push or a market pull, respectively. It can be assumed that the direct development of new ideas between biology and the market (biology to market push or market to biology pull) is encountered much less frequently (see Figure 2).

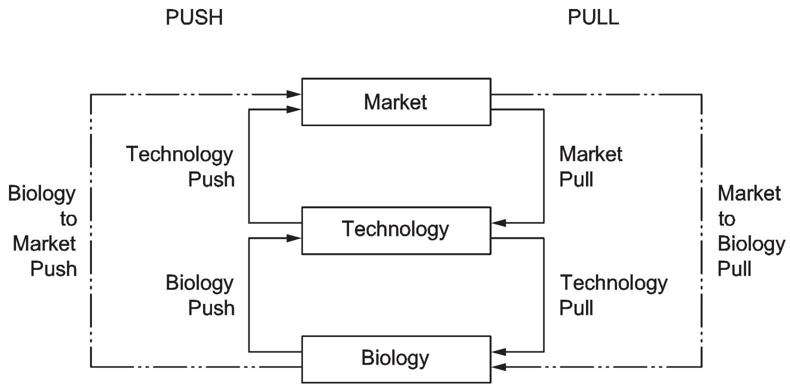


Figure 2 — Starting points in the development of new ideas[29]

The process of the biomimetic engineering is basically the same as the process after the starting point of the development of new ideas. A distinction shall be made when developing new ideas between a biology push and a technology pull[28].

Biology push

The starting point for the development of new ideas for a biomimetic development project in this case is knowledge from the field of biology and fundamental research (see Figure 3).

A biology push also makes it possible to develop approaches to solutions for future generations of technology (technology application) that only exist as a vision today.

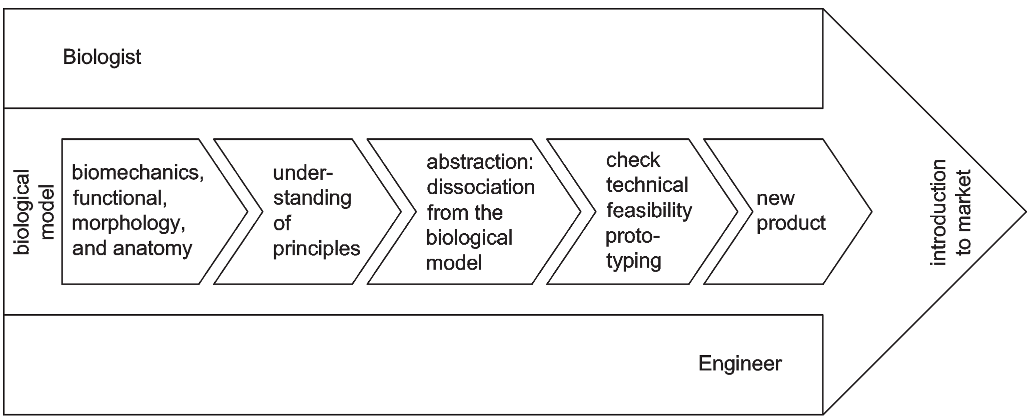


Figure 3 — Typical biomimetic development process for a biology push[28], modified according to Reference [30]

Technology pull

In contrast to a biology push, the starting point of biomimetic development in the case of a technology pull is a technical question or a technical problem. In this case, the purpose is to find biomimetic innovations for existing technical products that are often already successfully established in the market. The motivation behind a technology pull is to improve or refine an existing product or process (see Figure 4).

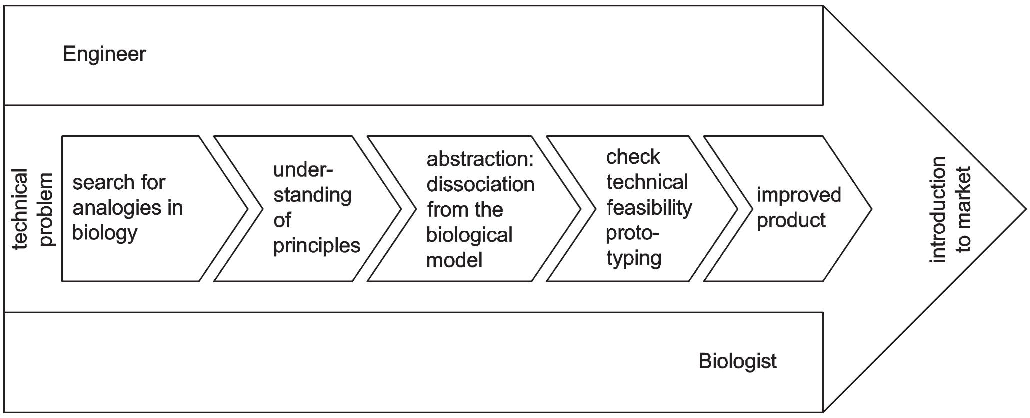


Figure 4 — Typical biomimetic development process for a technology pull[28], modified according to Reference [30]

In an analysis, the system or subsystem identified in the initial idea phase as a potential biological system is examined using procedures and methods from the natural sciences and/or engineering sciences. The results of these examinations are systematically catalogued and then evaluated in terms of their transferability. The particular procedures and methods depend in this case on the particular question posed, as well as on the object to be examined.

Functional analysis is a modelling process of the functional aspects of a system that explains the system architecture, structure, and behaviour[31]. During this process, the overall function of a system is decomposed into smaller sub-functions in order to transform the system main function to alternative sub-functions[32]. Some approaches suggest analysing the flows of the system as well[33]. Functional analysis of biological systems serves as an abstraction tool for biomimetic design processes[31][33]. The generation of functional models of biological systems is expected to enhance innovation and provide designers with better understanding of the design problem in general and of the functional mechanisms in particular[33].

In the framework of chemical analysis methods, for example, qualitative as well as quantitative analysis methods are used to identify the corresponding basic building blocks (molecules) or to determine the proportions of each substance.

Analysis methods from the field of material science provide information on the mechanical properties of materials (such as its elasticity, hardness, or ductility) or basic insights into the mechanical properties of biological tissues.

The goal of physical analysis methods (generally encountered in the form of experimental measurements) is to gain an understanding of a physical phenomenon, for example, relating to the kinematics and dynamics of a series of movements or relating to the generation of lift and propulsion on wings and fins.

Classic biological analysis methods include, among others, comparative morphology, in which preparation and dissection procedures provide information on the structure and geometry of an organism or parts thereof. The fields of functional morphology and biomechanics provide explanations for the relationships between the materials, forms, and functions. Physiological analysis methods provide systematic information on the method of operation of organisms or parts thereof (for example, active thermoregulation, circulatory systems, sensory systems, neural information processing, or neuromuscular motion control). In the framework of biological behavioural studies, populations or groups of individuals are analysed in terms of their mutual interaction or tested for their reaction to external stimuli (e.g. swarming behaviour).

In cases where the analysis method supplies data, the analysis is followed by a statistical analysis. The statistical analysis could use purely descriptive methods (for example, to determine certain values such as the arithmetic mean, mode, modality, standard deviation, variance, coefficient of variance, or to generate diagrams), as well as inductive methods (statistical tests such as significance tests, variance analyses, correlation and regression analyses, and time series analyses).

The goal of a mathematical analysis is to solve the mathematical equations (in the form of differential, difference, or integral equations) obtained from a physical and chemical model. This makes it possible to perform a quantitative analysis of the system to be examined and to forecast the possible system states, among other things. It is often necessary during the analysis to apply numerical methods such as the finite element method (FEM) or the computational fluid dynamics method (CFD).

5.3 Abstraction and analogy

An analogy is understood to be a similarity in the relationships between the parameters describing two different systems. The expression “similarity in the relationships between the parameters” is particularly important in this case and shall be differentiated from a “similarity between the parameters themselves”. The latter would lead to a copy. This interpretation of the term “analogy” is used in the context of the biomimetic innovation process for the analysis phase in particular.

In the biomimetic innovation process, the goal is to obtain the most complete analogy possible of the relevant problem in which it is possible to recognize the common and the different aspects in the corresponding analogies by comparing (mapping) the individual aspects (see Figure 5)[34].

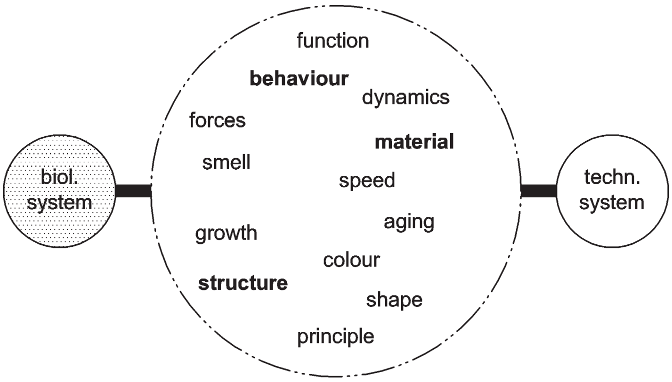


Figure 5 — Possible aspects used to compare analogies[28]

The biomimetic analogy model is built in several steps (see Figure 6, Figure 7, and Figure 8). In the first step, all possible facets of the analogy are listed (compilation of the aspects) based on an association that links the biological system to the technical problem. These aspects are not necessarily physical parameters. The compilation can also contain “soft factors” if these factors are suitable for use in a system comparison. The terminology should be selected so that it describes the biological system, as well as the technical system. To find such terms, it is generally necessary to abstract the biological system and the technical system.

It is useful to examine the biological and technical systems separately at first and then compile all aspects regardless of their relevance to the analogy. In the next step, the terms (aspects) found for both systems shall be compared to each other, and if necessary, new terms added.

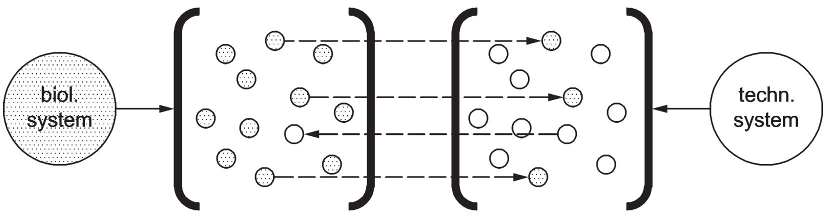


Figure 6 — Collecting aspects[28]

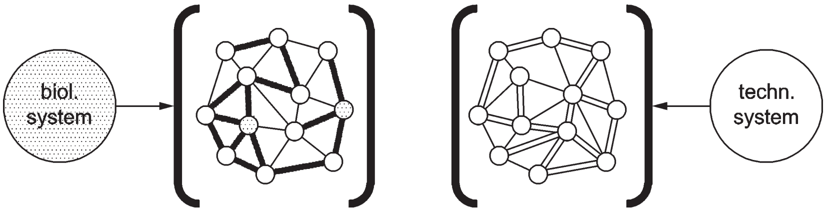


Figure 7 — Building the relationship networks[29]

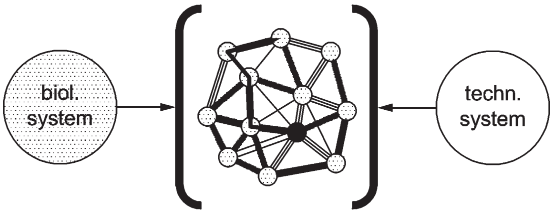


Figure 8 — Merging the relevant aspects[29]

The next step is to shed light on the relationships and interactions between the aspects found in the biological system and those found in the technical solution (relationship network of the corresponding analogies). Simplification and abstraction are also necessary in this step in order to reduce the relationship networks to the most essential relationships needed for the purpose of comparison.

In the third and final step, the relationship networks are superimposed in order to compare the biological and the technical systems as a whole. The process helps the user to become aware of the limits of an analogy, find useful analogies, and specify possible approaches to a solution.

The analogies and approaches found represent an abstract description of the possible solution. In the following phases of the biomimetic process, this solution shall be substantiated and specified in more detail.

5.4 Planning phase to invention

The actual development process begins with the planning and conception phase in which the technical goals and requirements of the intended application are specified in detail and examined in terms of their feasibility. For this purpose, technical specifications (lists of requirements) are created and converted to requirements specifications for each person involved in the project. The desired development of a process or product is divided into relevant subfunctions and approaches for the implementation of these subfunctions are pointed out. Suitable technical solutions are subsequently worked out and realized. In general, it is necessary to design several different variants that can be characterized accordingly and evaluated using suitable criteria. After that, a descriptive model can be created and simulations executed that allow extrapolation of the results to the conditions encountered in applications. A prototype is then produced as a result. The prototype is subsequently implemented in the planned technical application and its suitability evaluated by comparing the actual state to the target state and by performing an integral quality test and a vulnerability analysis. Based on these results, any potential optimizations are pointed out and put through the development cycle again by generating new and improved technical variants.

Even when the phases between planning and the invention only contain the steps normally taken in product and process development, biologists are being involved more and more frequently to help design these steps in real biomimetic projects. Due to the recursive nature and the complexity of biological systems, more in-depth observations and analyses of biological system are needed repeatedly, and biologists need to be involved here. Furthermore, it is becoming increasingly apparent that the ability to handle and abstract complex systems that are not fully understood down to the last detail, which is a prerequisite for a biologist, can also be beneficial for the development of technical systems. Knowledge of how a biological system interacts with its environment can then provide ideas for evaluating the sustainability of a biomimetic product, for example.

6 Implementation of biomimetics in the innovation approach

Biomimetics is already well anchored today in the scientific environment. Productive networks of different kinds have been built up and continue to develop dynamically.

In the future, biomimetics also needs to be anchored in education and professional training programs in addition to its constantly increasing presence in universities and extramural research institutions. In the area of applicaton-oriented industrial research and development, it will also become necessary to use biomimetics.

The development of structures, methods, and competencies for the interdisciplinary work in the field of biomimetics requires rigorous development. The transferal aspect of biomimetics needs to be increased significantly, primarily through increased integration of engineers, and especially engineers in application development. New forms and concepts for joint projects in which the formation of interdisciplinary teams (in the form of project houses, for example) and the exchange of personnel are carried out more intensively than in the past are examples of possible suitable measures.

To implement biomimetics in the innovation approach and to promote their application in practical applications, it is also important to announce examples of successful applications (best practice) and to win over more interest groups such as the decision-makers in business and politics.

Annex A
(informative)

Examples

A.1 Computer aided optimization (CAO)

a) **Function analysis of biological system:** growing tree **(+)**

b) **Abstraction from system to model:** adding of material to reduce areas of high mechanical stress **(+)**

c) **Transfer and application without using the biological system:** computer algorithms **(+)**

Conclusion: Biomimetics **yes**

An example for which a complete mathematical formulation has been obtained through the abstraction process is the CAO method[35] and components optimized by using this method. The CAO method is used to design technical components with high load capacities and long service lives. To accomplish this, the load-adaptive growth of trees is simulated on a computer with the help of special software for stress analysis so that the mechanical stresses can be homogenized and reduced during the design phase.

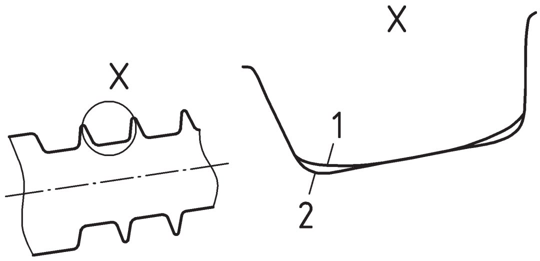
According to the three criteria in Table 1, the method shall be considered biomimetic because

a) the biological system is the growing tree,

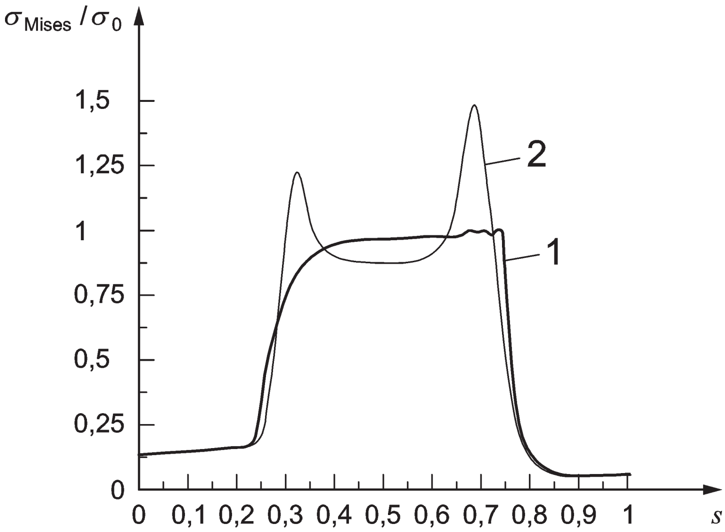
b) the complex cell division and cell growth process has been abstracted, and

c) the model has been implemented in simple algorithms and transferred to technical applications (it is used in industry to optimize technical components).

An example of such a biomimetic product is the orthopaedic screw (see Figure A.1). Like all technical products, its overall design is not based on a biological system, but in the mechanically critical area of the threads its design corresponds to the biological system of a tree through the application of growth principles.



a) Base of the thread



b) Local stress peaks

c) Screws

Key

1 optimized

2 not optimized

NOTE A minimal material volume at the base of the thread a) reduces local stress peaks b) and therefore significantly increases the lifespan of the component. c) above: optimized screw, withstood 5 000 000 load cycles and below: non-optimized screw, fatigue cracks after only 220 000 load cycles[29].

Figure A.1 — CAO optimization of an orthopaedic screw

A.2 Biomimetic spider silk

Biomimetic spider silk mimicking the amino acid sequence of the proteinaceous core of spider silk threads is an example of a biology push process in molecular biomimetics. As indicated by the name, this modern field of activity in biomimetics focuses on the molecular level of biogenic material and their structural elements, interaction, and assembly mechanisms, as well as the transfer of these aspects to generate innovative biomimetic materials. Thus, the level of abstraction from the biological system requires at least one aspect of either structure-function relations or assembly mechanisms at the molecular scale.

The development of engineered spider silk proteins (mainly spidroins) and its processing into a specific material morphology can be assigned to three distinctive steps of order: a) molecular biomimetics, b) recombinant protein production, and c) material processing.

a) **Molecular biomimetics**

   1) **Function analysis of biological system**: The amino acid composition and sequence of the silk protein core domain of a certain silk type is analysed by biomolecular methods and genetic engineering. Specific secondary structure motifs in the silk proteins coding for structural elements can be assigned to specific functions, such as elasticity or crystallinity. These specific motifs are translated back to genetic information (reverse translation), whereby the targeted structure-function relations are optimized and tailored for customized needs. With the help of a seamingless cloning strategy, a multimerized synthetic gene expression vector mimicking the natural silk protein is generated[36]. According to the three criteria in Table 1, this shall be considered biomimetics, i.e. molecular biomimetics. Biological system: amino acid composition of natural spider silk **(+)**

   2) **Abstraction from system to model**: special motifs are translated back to genetic information **(+)**

   3) **Transfer and application without using the biological system**: synthetic gene expression vector **(+)**

   Conclusion: Biomimetics **yes**

b) **Recombinant protein production**

   1) **Function analysis of biological system**: The production of the synthetic silk protein genes is performed biotechnologically in various suitable host systems like bacteria (e.g. *Echerichia coli* strains) or yeast (e.g. *Picchia pastoris* strains). Recombinant protein production does not involve any biomimetic approach, but is a pure biotechnology process ("white" biotechnology). According to the three criteria (in Table 1), this shall be considered no biomimetics but biotechnology. Biological system: synthetic gene **(-)**

   2) **Abstraction from system to model**: no abstraction **(-)**

   3) **Transfer and application without using the biological system**: production using biological host systems **(-)**

   Conclusion: Biomimetics **no**

c) **Material processing**

   The assembly of a natural spider silk thread is a highly controlled process depending on physico-chemical conditions, dynamically changing in the spinning duct of a spider. Spiders are able to adjust the parameters involved (such as phase separation by ion exchange, pH drop, and shear forces due to applied tension force) that influence the properties of the thread, mainly depending on the silk type requested. In addition, the spinneret defines the final silk morphology. It is possible to mimic certain aspects of the natural fibre spinning, either by developing new technical spinning processes or by adjusting existing ones[11]. The method mimicking the biological system the closest is called biomimetic spinning. It leads to fibres with mechanical properties similar to the natural spider dragline thread[37][38]. According to the three criteria in Table 1, this shall be considered biomimetics.

   1) **Function analysis of biological system:** Biological system: spinning duct of spider **(+)**

   2) **Abstraction from system to model:** certain aspects of physic-chemical conditions and of spinneret **(+)**

   3) **Transfer and application without using the biological system:** technical spinning process **(+)**

Conclusion: Biomimetics **yes**

Further examples of technical spinning processes with less mimetic aspects are wet spinning and microfluidics, both being able to produce fibres with defined properties close to a spider's thread. On the contrary, fibre spinning processes like electro-spinning rely on a mechanism different from that of the natural system and cannot be categorized as biomimetic.

A.3 Evolutionary algorithms

a) **Function analysis of biological system**: succession of generations of observable traits of organisms **(+)**

b) **Abstraction from system to model:** evolution **(+)**

c) **Transfer and application without using the biological system**: computer algorithms **(+)**

Conclusion: Biomimetics **yes**

In evolutionary algorithms, the "biological system" corresponds to generations of observable pools of organisms (fruit flies, bacteria, etc.) where environment changes are applied. The "model" is abstracted from the principles of mutation, recombination, and selection through which living organisms adapt to their environment over the course of generations. The model built on the biological systems is "applied" to computer algorithms used for optimization through successive generations/iterations in a given environment.

Evolutionary algorithms are also referred to for this reason as biomimetic optimization methods, but the objects optimized by them are not biomimetic objects (see also Table 1: results of evolutionary algorithms).

A.4 Fin ray

a) **Function analysis of biological system**: fin ray structure in fish fins **(+)**

b) **Abstraction from system to model:** 4-point junction linking two surfaces resulting in bending around the applied force **(+)**

c) **Transfer and application without using the biological systeml**: technical fins, e.g. as grippers **(+)**

Conclusion: Biomimetics **yes**

Fish fins respond unexpectedly when pressure is applied to the lateral side. When pressure is applied to one side of the tail fin, it automatically and passively bends against the direction of the force encountered. The patented Fin Ray® Effect is based on the structure of the individual fin rays[39]. The biological structure consists of two cartilaginous bands which meet at one end to form a triangle. Intermediate soft connective tissue keeps the two bands at a distance still allowing the bands to move relatively to each other. The technical structure consists of two flexible bands connected to each other at one end to form a triangle as well. Intermediate stays are connected to the bands at regular intervals by articulated joints. It is these stays that keep the bands at a distance and still allow the bands to move relatively to each other. When pressure is applied to the technical structure with Fin Ray® Effect, the structure passively bends around the pressure point. This flexible design was used to form gripper fingers which adapt to the shape of a workpiece when pressure is applied laterally (see Figure A.2) [SOURCE: Festo AG]. The fingers enclose objects of different shapes in a form-fitting manner without generating any point loads. Further possible applications of the passive Fin Ray® include use in the manufacturing of automobile seats, for example. When driving in a curve, a driver sitting in a seat equipped with a

Fin Ray® structure will be pressed into the side of the seat in which case, the longitudinal strut wraps flush around the driver without creating any pressure points and holds the driver in the seat.

a) b)

Figure A.2 — Adaptive fingers with Fin Ray® structure handling an object [Source: Festo AG]

A.5 Lotus-Effect®

a) **Function analysis of biological system**: self-cleaning surfaces of various plants **(+)**

b) **Abstraction from system to model:** self-cleaning is linked to physical (microstructures and nanostructures) and chemical (water repellence and surface tension) mechanisms **(+)**

c) **Transfer and application without using the biological system**: self-cleaning technical products **(+)**

Conclusion: Biomimetics **yes**

The development of technical products with self-cleaning surfaces and bearing the Lotus-Effect® trademark is a typical example of a biology push process in biomimetics (see Clause 5). The biological system in this case is the self-cleaning effect of the surfaces of plants[40]. The effect results from a microstructured and nanostructured surface, as well as from the water-repellant (hydrophobic) properties of the cuticle (outer waxy layer of plants) and the surface tension of water. In plants with self-cleaning surfaces, the outermost cells (epidermis) have 20 µm to 50 µm large papillae whose surfaces also have a 0,5 µm to 3,0 µm large wax structure. Since the basic principle of self-cleaning surfaces in nature is not linked to a biological system and is only due to physical (microstructures) and chemical (water repellence and surface tension) mechanisms, it was possible to abstract the principle from the biological system. The method of operation of self-cleaning surfaces was patented in 1998 throughout Europe and in most other countries outside of Europe (such as the USA). Like the biological system, technical products bearing the Lotus-Effect® trademark have a special microstructured surface and are highly water repellent. Water applied to these surfaces forms droplets with a high contact angle which roll off, removing resting dirt particles independent of their chemical composition.

A.6 Self-sharpening knife

a) **Function analysis of biological system**: incisors of rodents, alignment of enamel and dentine **(+)**

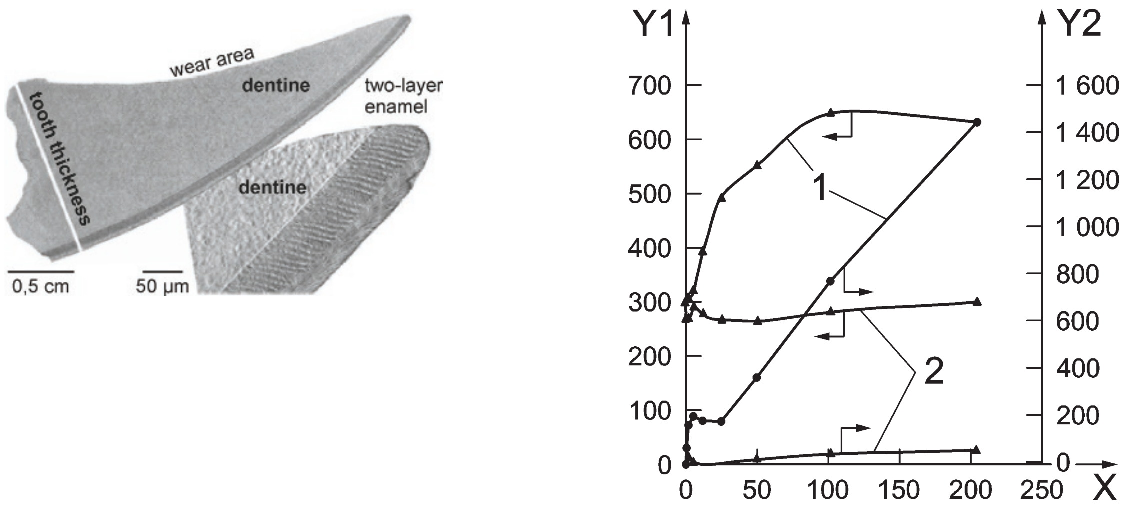
b) **Abstraction from system to model:** combination of a hard thin layer on an exposed surface that covers a softer main body that forms a cutting face **(+)**

c) **Transfer and application without using the biological system**: self-sharpening knife **(+)**

Conclusion: Biomimetics **yes**

An example of a technology pull process (see Clause 5) is the development of self-sharpening cutting tools based on a model of the incisors of rodents. The front sides of the incisors of rodents have less enamel than on the rest of the tooth (hardness: HV 400). The thin layer of enamel forms an exposed surface when cutting food. It covers and is stabilized by the dentine body. At the same time, the dentine is much softer than the enamel (hardness: HV 200) and wears much more quickly when cutting food. As a result, the enamel retains a high quality cutting edge and the tooth can even be re-sharpened by eating food [see Figure A.3 a)]. The abstraction can then be formulated when a self-sharpening cutting tool is produced using a combination of a hard thin layer on the exposed surface that covers a softer main body that forms the cutting face. The materials are matched to each other so that they form a long-lasting and self-sharpening cutting edge when exposed to the load conditions resulting from the cutting process.

A complete mathematical formulation of this relationship has not been developed to date but is still the object of scientific inquiry[41]. However, the abstracted knowledge already forms the basis for transfers into modern technology. It was possible to develop self-sharpening machine knives for application in strand cutting of mineral filled plastics. Engineers were able to develop a cutter that is simultaneously shock-resistant and permanently sharp. The cutting edge radius remains at a value of approximately 1 µm. The cutting forces acting on the biomimetic cutter are almost constant, in contrast to a conventional cutter, and there is much less wear [see Figure A.3 b)].



a) Incisor of the vole

b) Cutting force and specific wear volume

Key

1 conventional knife

2 biomimetic knife = Rodentics® cutter

X cutting path, in m

Y1 cutting force, in N

Y2 specific wear volume (1 000 µm^3/mm)

Figure A.3 — Incisor of the vole, cutting force, and specific wear volume as a function of the cutting path

A.7 Art Nouveau

a) **Function analysis of biological system**: e.g. plants and animals (+), e.g. minerals (-)

b) **Abstraction from system to model**: artistic design (±)

c) **Transfer and application without using the biological system**: no technical application (-)

Conclusion: Biomimetics **no**

A number of designs from the historical Art Nouveau period are based in design terms on models derived from nature. In these cases, the abstraction observed is usually an abstraction in the artistic sense, but there is no transfer to a technical application, which is an essential criterion according to Table 1.

A.8 Fibonacci sequence

a) **Function analysis of biological system**: e.g. shell spirals, sunflowers **(±)**

b) **Abstraction from system to model:** Fibonacci sequence as mathematical or geometric principle **(-)** as based on nature observation **(+)**

c) **Transfer and application without using the biological system**: no technical application

Conclusion: Biomimetics **no**

The Fibonacci sequence ($x_{n+2} = x_{n+1} + x_n$, for $n \geq 0$) is frequently encountered in nature. The quotient of two large, sequential numbers in this sequence (as n goes to infinity) forms the well-known golden ratio (x_{n+1}/x_n)[42]. The golden spiral, which is based on the Fibonacci sequence, is encountered in the spiral-shaped calcareous shells of some animal species. These shells have a spiral pitch similar to that of a nautilus shell. The golden angle is created when a full circle is sectioned according to the golden ratio and is equal to approximately 137,5°. This angle is found in sunflowers, in the arrangement of pine needles on young branches, and in the petals of roses, for example. In the case of the sunflower, the deviation from the golden angle is less than 0,01 %. It has not been proven if the golden ratio design rule is based on observations of nature or if it is the result of the application of a mathematical or geometric principle. The deciding factor in the resulting evaluation as “non-biomimetic” is the lack of technical applications at this point of time.

A.9 Olympia roof

a) **Function analysis of biological system**: independent development **(-)**

b) **Abstraction from system to model**: independent development **(-)**

c) **Transfer and application without using the biological system**: independent development **(-)**

Conclusion: Biomimetics **no**

The Olympia roof in Munich is often cited as an example of biomimetic architecture. The model for this structure was the German pavilion at the World Expo in Montreal in 1967. Both of these designs were based on the investigation of a physical/technical phenomenon, the minimal surface, which had been thoroughly examined in the context of shape formation processes in nature. The similarity of the Olympia roof to the webs of various spiders cannot be denied. However, the Olympia roof is a stiff construction for the most part, which clearly distinguishes it from the extremely elastic spider web. For this reason, this type of architecture cannot be considered biomimetic architecture.

A.10 Reinforced concrete

a) **Function analysis of biological system**: plant stems **(+)**

b) **Abstraction from system to model**: no abstraction, not understood **(-)**

c) **Transfer and application without using the biological system**: ferroconcrete **(±)**

Conclusion: Biomimetics **no**

Reinforced concrete is one of the most important composite building materials in the world. It realizes the same static principles as those found in the stems of plants, namely a base matrix with embedded reinforcement. Although the fact that ferro concrete was patented by a French gardener would appear to indicate it is a biomimetic product and it cannot be ruled out that plants inspired the invention in terms of its principle of operation, reinforced concrete cannot be considered a biomimetic product. The principle of composite structure found in plants had not been abstracted or even understood in detail at that time.

A.11 Soap-film analogies

a) **Function analysis of biological system**: independent development **(-)**

b) **Abstraction from system to model:** independent development **(-)**

c) **Transfer and application without using the biological system**: independent development **(-)**

Conclusion: Biomimetics **no**

The soap-film analogy is used in the context of determining the shape and form of a membrane under tension (such as a tent, for example). Surfaces optimized in this manner approximate theoretically minimal surfaces. Soap films are in a homogeneous, isotropic stress state, which means the stress is the same at every location and in every direction. The soap-film analogy is based solely on fundamental physical principles. The "biological system/model" criterion required according to Table 1 is not fulfilled in this case.

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