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Biomimetics — Biomimetic materials, structures and components

Biomimétisme — Matériaux, structures et composants biomimétiques

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Contents

Page

Foreword

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

Introduction

The increasing complexity of technical solutions and products requires new approaches. Classic research and development methods and innovation approaches often reach their limits, especially in the development and optimization of materials, structures, and components. The identification of suitable biological principles and their transfer to technical applications in the sense of biomimetics, therefore, can make an important contribution to the development of functional, adaptive, efficient (in terms of resources), and safe (in terms of toxicity to humans and the environment) materials, structures, components and manufacturing techniques.

Biomimetics — Biomimetic materials, structures and components

1 Scope

This International Standard provides a framework of biomimetics for the development of materials, structures, surfaces, components, and manufacturing technologies.

This International Standard specifies the principles of biological systems, and especially the performance of biological materials, structures, surfaces, components, and manufacturing technologies that provide the motivation and reasons for biomimetic approaches. It specifies the methodology based on analysis of biological systems, which lead to analogies, and abstractions. The transfer process from biology to technology is described based on examples of biomimetic materials, structures, surfaces, components, and manufacturing technologies. This International Standard describes measurement methods and parameters for the characterization of properties of biomimetic materials. This International Standard provides information on the relevance of biomimetic materials, structures, surfaces, components, and manufacturing technologies for industry.

This International Standard also links to other subareas in biomimetics because fundamental developments in materials, structures, surfaces, components, and manufacturing technologies often form the basis for a wide variety of additional innovations. It provides guidance and support for all those who develop, design, process, or use biomimetic materials, structures, surfaces, components, and manufacturing technologies. This International Standard can also serve for those who want to learn about and investigate these topics.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 18458, *Biomimetics — Terminology, concepts and methodology*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18458 and the following apply.

3.1
adaptivity
ability to adapt to variable environmental conditions

3.2
efficiency
relationship between the useful outputs to all inputs of a system

3.3
generative manufacturing process
manufacturing process in which three-dimensional components are produced, for instance, by applying material layer-by-layer

Note 1 to entry: These technologies can be used in four different levels of manufacturing:

— Concept model (additive manufacturing): A mechanical load cannot be applied to these models and they only serve to provide a three-dimensional view.

- Functional models (additive manufacturing): These models have properties similar to those available in the components manufactured later on in mass-production.
- Tools (rapid tooling): Tools are created that can be combined with other manufacturing processes.
- Low volume production (rapid manufacturing): The properties of the geometries manufactured correspond to those desired in actual use.

3.4
gradient transition
gradual transition
direction-dependent, continuous change of a chemical, physical, or mechanical property

Note 1 to entry: Biological materials are often characterized by gradual transitions in terms of their physical and mechanical properties, which are achieved through structural changes at various hierarchical levels, among other things.

3.5
compatibility
recyclability and adaptability of a material flow or a technology in the environment

3.6
modularity
composition of an overall system from individual modules

3.7
multifunctionality
structure and properties of a material and component allowing several functions necessary for the organism or technically desired to be realized at a high level and in equilibrium

3.8
redundancy
existence of functionally comparable systems, whereby one system alone is sufficient to maintain the corresponding function (multiplicity in systems)

3.9
resilience
fault tolerance
tolerance of a system to malfunctions or capacity to recover functionality after stress

3.10
Self-X property
property and information existing in a material or on a surface proceed processes autonomously without requiring special control

Note 1 to entry: Self-X properties are widespread in biological materials and surfaces and are of great interest for transfer to technical products. Examples include self-organization, self-assembly, self-repair, self-healing, self-cleaning, and self-sharpening.

3.11
stereoregularity
tacticity
certain geometric regularity in the molecular structure of polymer chains

Note 1 to entry: Macromolecular materials with identical chemical compositions can have significantly different mechanical properties due to differences in the spatial arrangement of their atoms and groups of atoms. In chemical production techniques, the molecular geometry of polymer chains is determined during polymerization by the reaction temperature selected and the catalyst used.

Note 2 to entry: A classic example from nature is polyisoprene, which can be elastic (natural rubber), as well as hard (balata, gutta-percha).

4 Abbreviated terms

AES	Auger Electron Spectroscopy
AFM	Atomic Force Microscope
CT	Computed Tomography
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
GC	Gas Chromatography
GC-MS/MS	Gas Chromatography-tandem Mass Spectrometry
GPC	Gel Permeation Chromatography
HPLC	High performance liquid chromatography
IR	Infrared Spectroscopy
LC-MS/MS	Liquid Chromatography-tandem Mass Spectrometry
MALDI-MS	Matrix Assisted Laser Desorption/Ionization-Mass Spectrometry
NMR	Nuclear Magnetic Resonance
OM	Optical microscope
SEM	Scanning Electron Microscope
SEM-EDS	Scanning Electron Microscopy-Energy Dispersion Spectroscopy
SIM	Structured Illumination Microscopy
SIMS	Secondary Ion Mass Spectrometry
SPM	Scanning Probe Microscope
TEM	Transmission Electron Microscope
TOF-SIMS	Time-of-Flight Secondary Mass Spectrometry
UVVIS	Ultra Violet Visible
XPS	X-ray Photoelectron Spectroscopy
XRF	X-ray Fluorescence Analysis

5 Biological materials

5.1 Characteristics

5.1.1 General

The terms material and structure sometimes have different meanings in biology and in technology. Classic technical materials are often considered to be homogeneous, so that it is reasonable and permissible to assume in calculations and for manufacturing purposes that the model is isotropic.

Technical materials rely mostly on chemistry for their properties whereas biological materials rely on structure and are almost invariably composite.

Owing 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. For this reason, the term “material” is used in the following as a general term for all biological materials with their respective structures.

Some characteristics of biological materials that are relevant to biomimetic implementations are listed in Table 1.

Table 1 — Characteristics of biological materials

Characteristics	Biological Example	Explanations
Properties		
Multifunctionality	**Wood**: integration of water pipes, strength, damping, storage, among other things	Biological materials are often multicriteria-optimized and possess a high-function density, and they often combine supposedly conflicting functions.
Hierarchy	**Wood**: at least five structural levels, from the molecular structure of the cell wall to the structure of the tree trunk	A special feature of the hierarchical design of biological materials is that structural or (bio) chemical changes in one level lead to specific adaptations in the other hierarchy levels. This level spanning adaptability permits a wide variety of different functions.
Fault and failure tolerance (resilience and redundancy)	**Bones**: ample breaking strength, tolerance to micro-cracks, crack stoppers	Biological materials can handle a high level of faults and damage before they fail as a whole.
Self-X	**Rubber tree**: self-repair **Teeth of rodents**: self-sharpening **Surface of leaves**: self-cleaning	Biological materials are able to generate and maintain their complex functions autonomously, meaning, without external control.
Adaptivity	**Bones**: load adaptivity **Plant motion**: for example, nastic movements and tropism	Biological materials can react to changes in environmental conditions by changing their form or through growth and restructuring processes.
Compatibility	**Walls of plant cells**: consist almost exclusively of carbon, oxygen and hydrogen	Availability/biodegradability of the biological building blocks. The waste products produced are rarely pollutants. The waste products are in fact biodegradable and recyclable.
Modularity	Organization of **organs**: composition of several different tissues	Repetition of identical basic units at different hierarchical levels.
Lifespan according to needs	**Tree:** dropping of leaves	Important properties are maintained through renewal. The lifespans of individual components match, and the components are renewed.
Gradual transitions	Many biological materials, for example, plant stems (e.g. fibre/substrate tissue transitions), long bones (such as cortical/cancellous bone transitions), bone/ tendon/ muscle transitions	Prevention of sudden transitions between properties to increase the lifespan and tolerance to damage.

Table 1 *(continued)*

Characteristics	Biological Example	Explanations
Manufacture		
Growth	Many biological materials, as well as, for example, **self-cleaning leaf surfaces:** self-assembly of the genetically coded wax molecules	Biological materials and organisms are created through genetically controlled self-organization. Living organisms are formed using molecules, organelles, cells, tissues and organs, i.e. by growing from small to large.
Opportunism (use of readily available resources)	**Photosynthesis**: utilization of solar energy	In biology, a few predominantly light elements that are available locally and in large quantities are used (C, H, O, N, S, Ca, P, Si).
Mild environmental conditions	**Enzymes**: catalysis at ambient temperatures	Adequate conversion of material at low ambient temperatures.

5.1.2 Biological materials: multifunctional, fault-tolerant, modular, and adaptive

The characteristics of biological materials listed in Table 1 can be divided into properties and manufacturing characteristics. The properties of biological materials include multifunctionality, fault and failure tolerance, the Self-X properties, adaptivity, and modularity, only to name a few. Manufacturing characteristics such as biological growth, meaning, genetically controlled self-organization from the level of molecules to the level of the living organism itself, and resource-oriented construction under mild environmental conditions are further examples of the abilities of biological materials. Furthermore, biological materials have a limited lifespan. After the organism dies, they are generally completely broken down and return into the natural material cycle. When applied to the “lifespans” of technical applications, this property is also of interest and is studied in biomimetic research and development projects.

Tree trunks are a biological example of multicriteria optimization in nature in which numerous and sometimes conflicting functions are executed simultaneously with high reliability. They combine mechanical stability against working loads (such as the weight of its own tree trunk and crown, as well as wind and snow loads) with transport functions for water and metabolic products, storage functions, and photosynthesis[1].

Another characteristic of living organisms is their ability to adapt to variable environmental conditions (adaptivity), which enables them to survive. The high tolerance of biological materials to damage shall also be mentioned in this context, as well as the ability of many living organisms to quickly and efficiently repair damage. The capability for self-repair and adaptivity are characteristics of living organisms that are particularly interesting for biomimetic developments[2].

5.1.3 Technical components: monofunctional, durable, with a limited ability to adapt

Technical components are generally developed and optimized with the focus on a single dominant function. In technical systems such as vehicles, though, they often fulfil many other boundary conditions and constraints such as a limited design space, multiple mechanical loads, connection of additional components, manufacturing and component joining restrictions, but also limited development times. This often results in compromised solutions or oversized components that are not ideal. Components are often manufactured based on the material, meaning, they are manufactured from the large (work piece blank) to the small (product), and are not adaptive or self-repairing as a rule. The durability of a component can be problematic once it has passed its normal lifespan, and it is often difficult to return it to geo-ecological material cycles.

While living organisms shall function continuously in order to ensure their survival and successful reproduction, machines can be taken out of operation for maintenance, modification, and reconstruction. It is therefore possible to optimize machine components quickly and for a specific function, and all resources, materials, and technologies available (e.g. high temperature processes in metal processing and silicon technologies) can be used for this purpose. In comparison to evolutionary processes, these conditions allow very short development stages, and sometimes old technologies are even completely replaced by new technologies (for example, the replacement of analog technologies by digital technologies).

These differences cause biological evolution and human technology to reach very different solutions to comparable “problems” in some cases even though they are subject to the same physical laws and share the same physical environment[3].

5.2 Performances

Performances of biological systems are rich in variety. Examples of 151 biological systems are shown in Table 2[4]. Performances of biological systems are classified into eight categories:

a) materials;

b) process;

c) Self-X;

d) sensors;

e) hydrodynamics;

f) saving energy/saving resources;

g) adaptability to the environment;

h) behaviour/ecology.

The categories contain 56 kinds of specific examples. 43 expected fields of applications are summarized in Table 2 to see the overview of performance of biological systems. Especially, the interfaces of biological systems demonstrate particularly interesting properties that have a high potential to lead to new technological developments; examples are optics, anti-reflection, wettability, adhesion, fluid dynamics, surface tension, self-organization, self-cleaning, lift, fluid resistance, friction control.

Some examples of biomimetic products are introduced in Annex A.

Table 2 — Performances of biological systems and possible applications in different categories

No.	Performances	Biological example	Possible application areas
a) Materials			
1	Anti-reflection, structural colour, photonics	Morpho butterfly (see A.9), moth eyes (see A.10), blue damselfish, maranta, fish scales (see A.4)	Liquid crystal, decoration, electronics, functional film, cosmetics
2	Luminescence	Fire fly, squid, jellyfish	Automobile, household electric appliances, decoration
3	Lightweight structure	Bamboo, plant stem, winter horsetail (see A.6), boxfish, diatom, bone	Architecture, automobile, structural material
4	Wettability	Lotus (see A.12), land snail, wings of butterfly, wings of cicadas, rose, Namibian desert beetle, pitcher plant	Texture, coating material, architecture, automobile, glass, water harvesting, (marine industry)
5	Mechanical properties	Abalone(see A.3), bone, tree, bamboo, spider silk	Texture, architecture, medicine, sports industry
6a	Dynamics of a bistable system	Venus flytrap	Switching structures
6b	Torsional buckling	Strelitzia	Architecture

Table 2 *(continued)*

No.	Performances	Biological example	Possible application areas
7	Adhesion and attachment	Blue mussel, gecko (see A.11), leaf beetle, land snail, burdock seeds, octopus suckers, sea urchin, slime mould	Architecture, medicine, manufacture
8	Fluid dynamics	Shark skin, dolphin, bluefin tuna, penguin, bird, dragonfly, maple seeds	Aircraft, ship, household electric appliances, coating materials, sports industry
9	Electrical properties/ isolator, electricity generation	Electric eel, dried shells, dried trees	Ceramic industry, electric industry
10	Impact absorption	Pomelo, cashew, joint, rhinoceros beetle	Automobile, medicine, defence industry
11	Bio-template	Tobacco mosaic virus, DNA, wings of butterflies, spirulina	Electronics, semiconductor industry
12	Tube structure	Mosquito, butterfly, wharf roach	Medicine
13	Surface tension	Whirligig beetle, backswimmer	Coating materials
14	Unidirectional	Mouth of snake, earthworm, bee, pitcher plant	Machine parts
b) Process			
15	Bio-mineral	Shells, teeth, bone, diatom	Medicine, decoration, ceramic industry
16	Photosynthesis	Plant	Energy industry, agriculture, food industry
17	Organic synthesis	Spider silk, blue mussel, plant wax, pine resin, Para rubber tree, ligaments of grasshopper (see A.2)	Medicine, chemical industry
18	Processing	Shipworm	Civil engineering
19	Metabolism	Cellulose degradation, silk, amino-acid fermentation, alcohol fermentation, entomophagy, stockbreeding	Food industry, energy industry, plastics industry
20	Micro-mist	Bombardier beetle	Machine parts, internal-combustion engine, coating materials
21	Abscission	Leaf fall	Manufacture
22	Scattering	Poppy	Household electric appliances
c) Self-X			
23	Self-organization	Organisms	Medicine, electronics, films
24	Self-healing, self-repair	Skin, bone, teeth, lizard, plant leaves, shark teeth, planarian	Medicine, coating materials, automobile, electronics, household electric appliances
25	Self-assembly	Cell membrane	Medicine, coating
26	Self-cleaning	Lotus leaf, land snail, wings of butterflies, wings of cicadas	Architecture, automobile, coating materials
27	Self-sharpening	Teeth of rodents (see A.5)	Tools
d) Sensor			
28	Ocular vision/visible light, infrared, specific wavelength	Eyes, compound eyes, photoreceptors in crown-of-thorn starfish, tube feet urchin, *Melanophila* beetle, cabbage white butterfly	Sensor, architecture, household electric appliances, automobile, aircraft
29	Olfaction	Ant, dog, insect, deep-sea fish	Sensor, household electric appliances, automobile

Table 2 *(continued)*

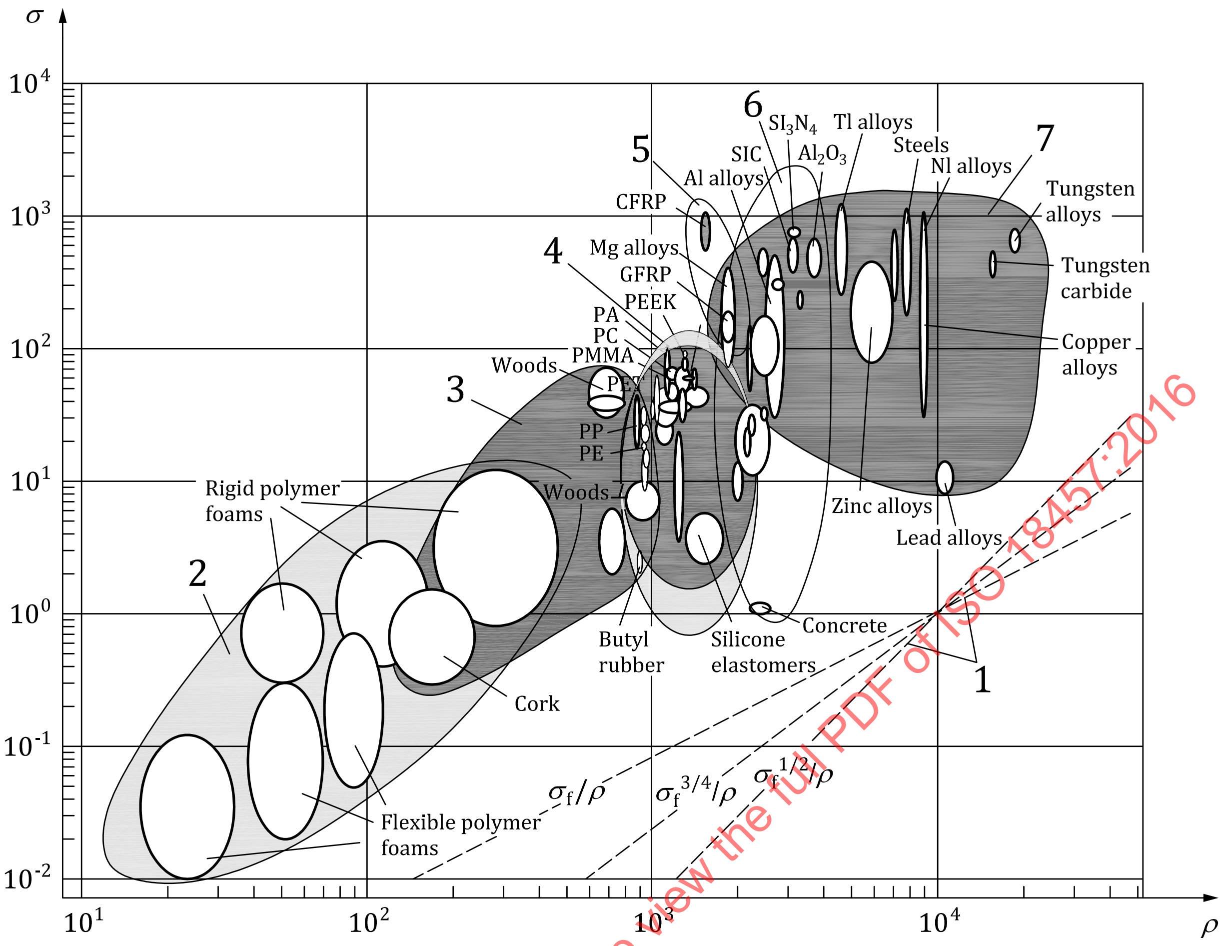
No.	Performances	Biological example	Possible application areas
30	Tactile sense, mechanoreceptor	Cat whiskers, gravity sensors of plant	Sensor, household electric appliances, automobile
31	Chemosensation	Ant, fly, bee	Sensor, food industry
32	Auditory sense/ultrasonic waves, low frequency	Bats, longhorn beetle, dolphin, gecko	Aircraft, sensor, agriculture (pest control)
33	Magnetic sensor	Migratory bird, sea turtles, pigeon, spiny lobster, shark, honeybee	Aircraft, sensor, ship
34	Force sensor	Cricket	Sensor, household electric appliances
e) Hydrodynamics			
35	Buoyancy	Nautilus, cuttlefish, jellyfish	Ship
36	Lift	Wings of bird, dragonfly	Aircraft, power generation
37	Driving force	Jellyfish, *Paramecium*	Robot industry
38	Fluid resistance	Shark skin, dolphin, Bluefin tuna, penguin, kingfisher, boxfish, wings of owl, eel	Ship, sports industry, automobile, aircraft
f) Saving energy, saving resources			
39	Friction control	Snake, sand skink, joint	Machine parts, robot industry, automobile, medicine, welfare
40	Temperature control	Shade of trees, polar bear, swan, skunk cabbage, zebra, anthill, mammalian sweat, transpiration	Architecture, texture, automobile
41	Moisture control	Anthill	Architecture
42	Circulatory (sustainability)/ adaptability for recycling, degradability	Food web, leaf fall, fungi, termite	Energy industry, agriculture
g) Adaptability to the environment			
43	Desiccation tolerance	Plant stomata, chironomid, cactus	Medicine, texture
44	Cold-resistance	Polar bear, *Trematomus* fish, *Tenebrio* beetle, reindeer	Medicine, food industry, battery
45	Acid or alkali tolerant	*Helicobacter pylori*, microbes in submarine volcano, bacteria in hot spring/alkaliphile	Fuel cell
46	High-temperature tolerance	Microbes in submarine hydrothermal polymetallic ore	
47	High-temperature use	*Eucalyptus*, *Banksia*, *Melanophila* beetle	Sensor
48	Ultraviolet resistance	Edelweiss	Cosmetics
h) Behaviour, ecology			
49	Mimicry/colour, shape, chemical camouflage	Octopus, flatfish, squid, chameleon, insects like dead leaves, seahorse, mantidfly, *Kallima* butterfly, termite eggs	Defence industry, decoration, pest control
50	Manipulation	Elephant nose, octopus arm, fish's fin	Robot industry, machine parts, tools
51	Energy saving	School of fish, flock of birds/sardines, migratory birds	Aircraft, automobile
52	Clash avoidance	Swarm of bees/ants, bats	Aircraft, automobile
53	Pollinator	Insect, bat	Agriculture, food industry

Table 2 *(continued)*

No.	Performances	Biological example	Possible application areas
54	Sociality	Honeybee, colony of social insects	Agriculture, food industry
55	Natural enemy	Spider mite vs. predator mite, biopesticide	Biotic pesticide, agriculture
56	Defence	Zebra, shoal of sardines, shoal of striped eel catfish	Design, decoration

The performance of biological materials as compared to technical materials can be illustrated quantitatively using material properties diagrams created based on information from Ashby[5] (see Figures 1 to 4). Since cells produce biological materials, they are assembled from the molecule upwards. This requires that the molecules can assemble themselves into larger structures and that the resulting structures can themselves assemble into even larger structures. Thus, a tree can have as many as 15 levels of hierarchy of structure. The interface between each level of the hierarchy controls the transfer of loads between the levels, introducing a degree of control of material properties, which is unattainable in technical materials (see Figure 5).

A comparison of specific properties of biological and engineering materials is given in Figure 5. Both groups of materials are plotted, showing that they cover nearly the same ranges except for high performance ceramics and alloys (constructed from data by Wegst and Ashby)[5][6].



Key

ρ density (kg/m³)

σ strength (MPa)

1 guidelines for minimum mass design

2 foams

3 natural materials

4 polymers and elastomers

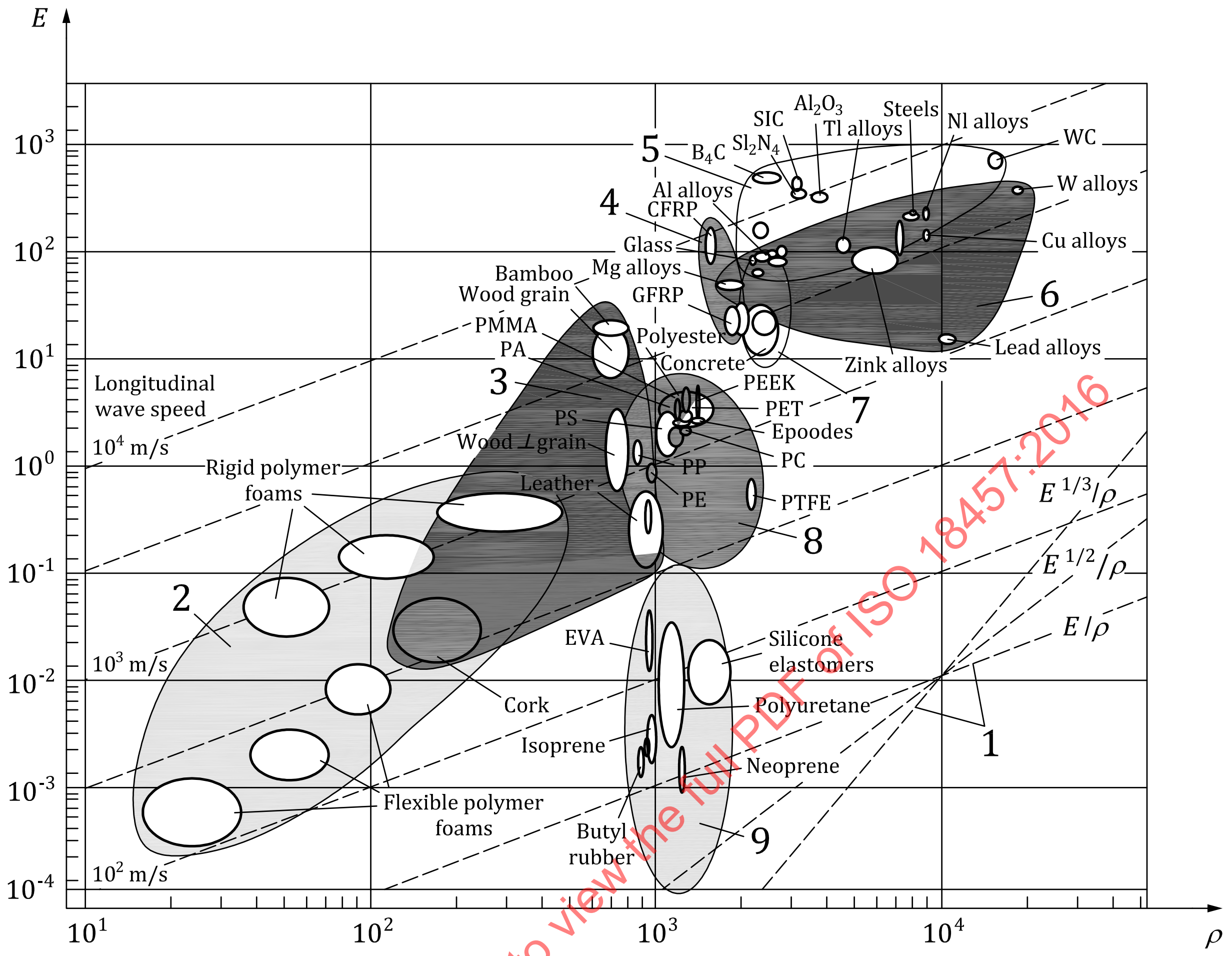
5 composites

6 ceramics

7 metals

NOTE In the diagram, the materials strength is graphed against the density to identify materials with a high resistance to plastic flow stress (permanent deformation) and the lowest possible weight, for example.

Figure 1 — Material properties diagram based on density and strength from Reference [5]



Key

ρ density (kg/m3)

E Young's modulus (GPa)

1 guidelines for minimum mass design

2 foams

3 natural materials

4 composites

5 technical ceramics

6 metals

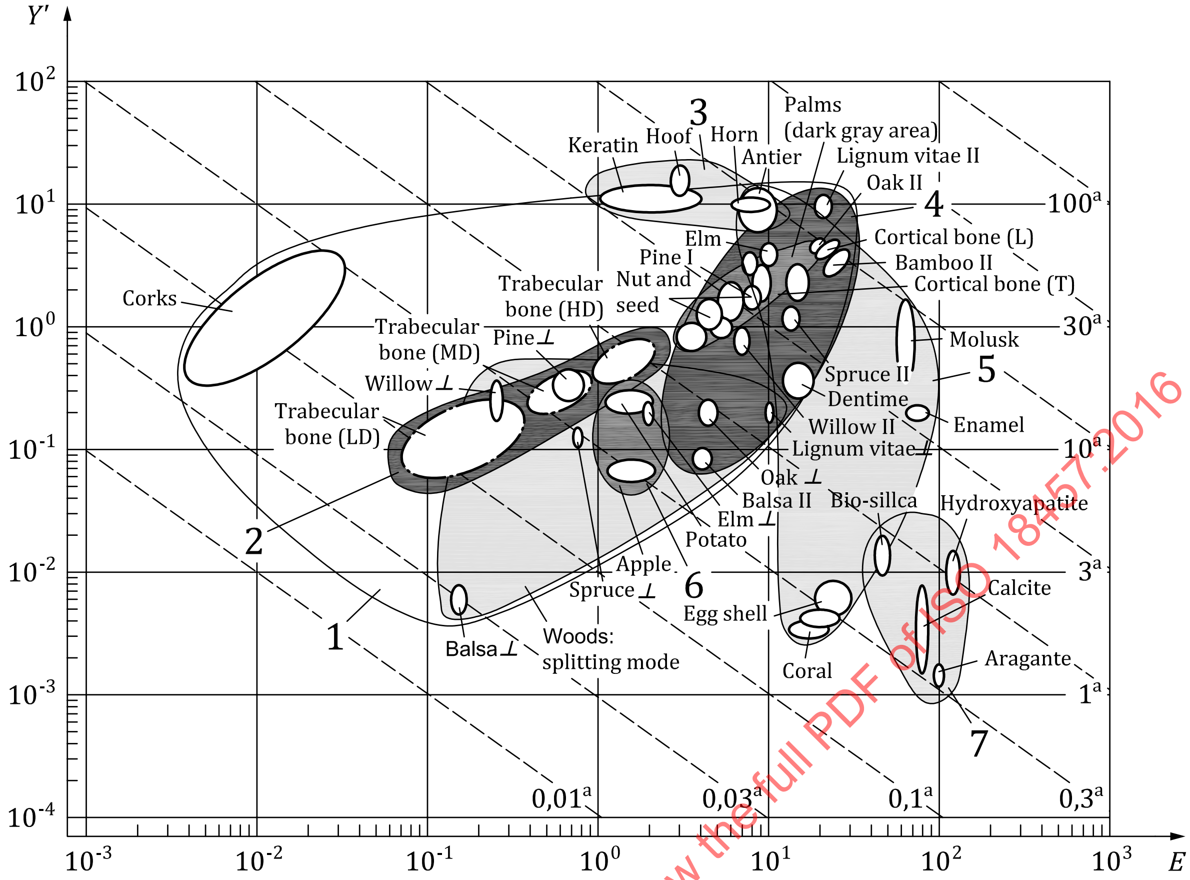
7 non-technical ceramics

8 polymers

9 elastomers

NOTE In the diagram, the modulus of elasticity is graphed against the density to identify materials with high stiffness and the lowest possible weight, for example.

Figure 2 — Material properties diagram based on density and elasticity from Reference [5]



Key

E Young's modulus (GPa)

Y' toughness (kJ/m2)

1 natural cellular materials

2 trabecular bone

3 soft tissue

4 woods

5 dense mineralized tissue

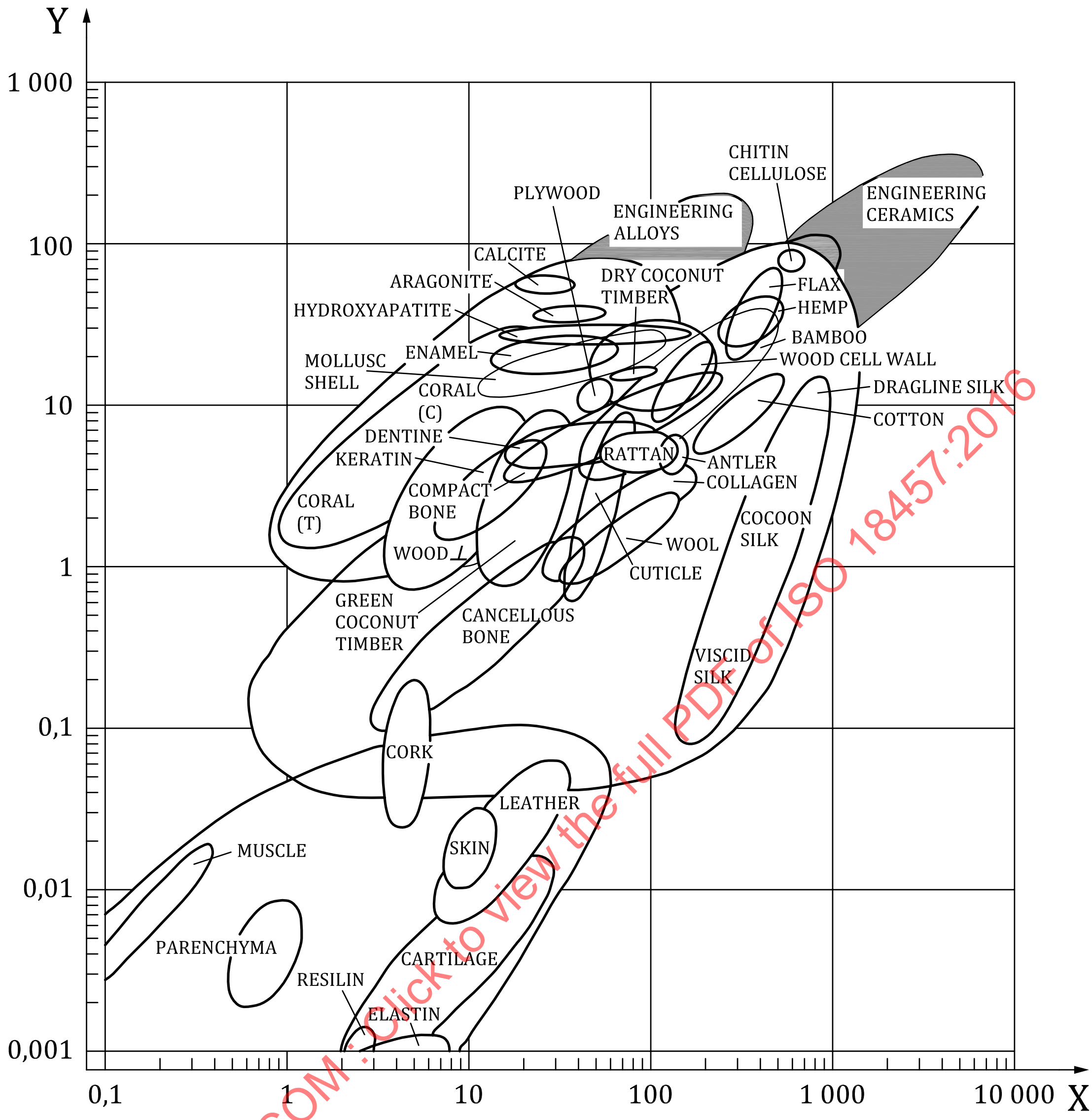
6 parenchyma

7 bio-ceramics

a Fracture toughness.

NOTE In the diagram, the toughness is graphed against the modulus of elasticity to identify the stiffest possible materials with a high resistance to progressive crack growth for fatigue-resistant components, for example.

Figure 3 — Material properties diagram based on elasticity and toughness from Reference [5]



Key

X specific strength

Y specific stiffness

Figure 4 — Specific stiffness vs. specific strength of biological materials (information from Reference [6]) overlaid onto technical materials (information from Reference [5])

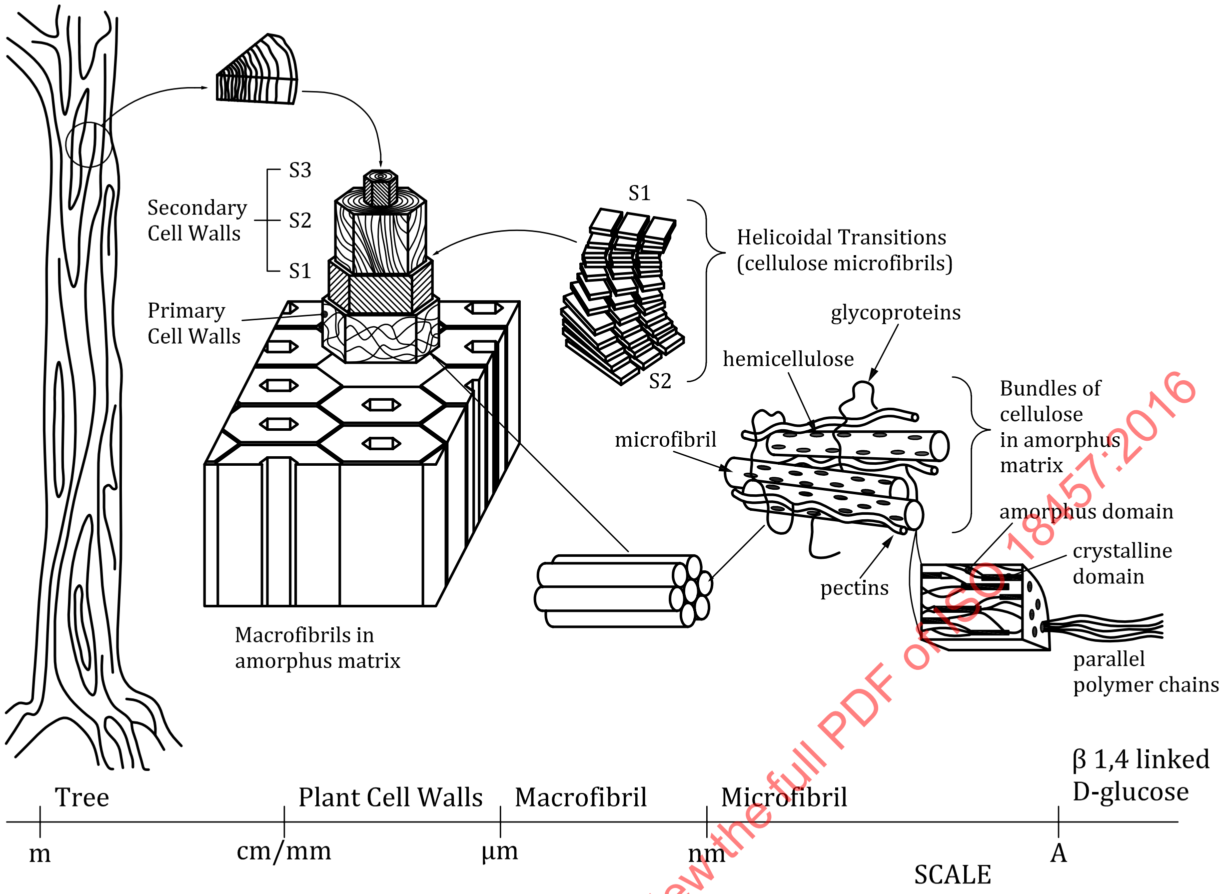


Figure 5 — Typical analysis methods at various hierarchy levels shown at the example of wood/fibres (see B.2)[8]

6 Methodology of biomimetic material and component development

6.1 Analysis

Biological materials are generally composites, and their hierarchical and modular design requires analysis at several different length scales (see Figure 5).

Newer light microscopic methods are suitable for studying biological materials, including living tissues. These methods are collectively referred to as “multiphoton microscopy”, “higher harmonic generation (HHG)”, or “3D-SIM microscopy”. The resolution of these methods is significantly below the Abbé limit of classic light microscopy of approximately 200 nm[9][10][11].

The high variability of properties of biological materials requires a relatively large number of samples to be taken. Macroscopic analyses in particular are difficult due to local variations in the properties and the resulting lack of homogeneity in a sample object. The possibility that this variability serves a certain function shall be considered and shall not be “averaged out” (for example, in the case of the effective contact area of a rough surface). When analysing and assessing a specific structure/property relationship, though, it is also necessary to take the multifunctionality of biological systems into account.

If possible, the analyses should be suitable for the examination of the materials in their native state (humidity, pressure, temperature, other ambient conditions). For this reason, the existing testing standards can only be used as basic standards when designing a test setup. As a general rule, it is impossible to apply the testing standards directly since biological materials usually place very specific requirements on the analysis methods in terms of the sample geometry, ambient conditions, etc.

Biological research frequently does not answer the questions posed by engineers. However, the techniques biologists use are relevant and are contained in Annex B.

6.2 Examination of analogies

The focus of a biomimetic process is placed on the examination of an analogy or a similarity between a biological system and a technical target system. Before the biological system is used and its details are transferred, the model shall be tested and analysed systematically. These tests and analyses should determine if the function, parameters, parameter ratios, and quality criteria are equally relevant to the biological system — reduced to the actual object to be transferred — and the technical target system (see Figure 6).

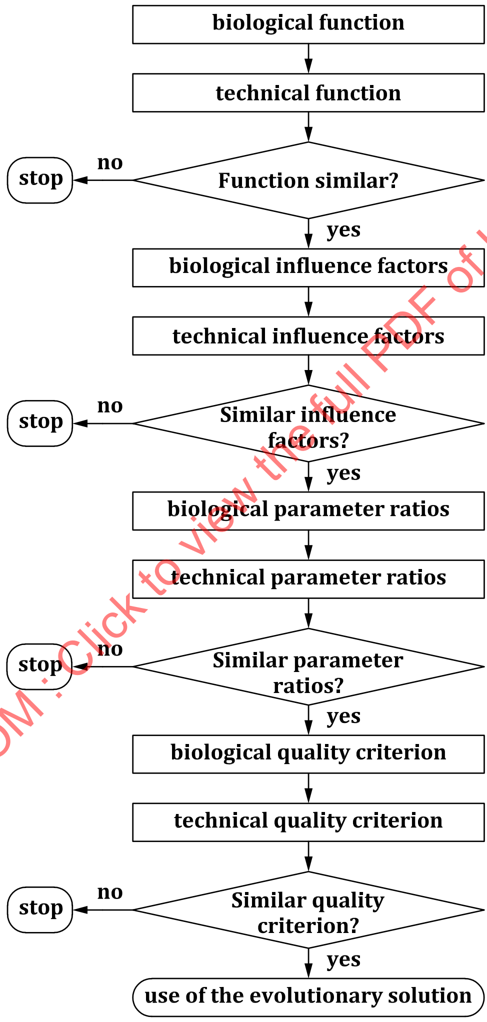


Figure 6 — Algorithm for examination of the analogy (The figure is revised according to Reference [12])

The first step of the examination of the analogy is to check if the function of the biological system matches the function of the technical target system. A function in this case is a task that a certain object in the biological or technical context shall perform.

In the next step, it is necessary to identify all parameters and determine their relevance to the problem. When a factor will not be taken into account due to its lack of relevance, a reason should be provided. These parameters are determined intuitively or systematically, for example, based on (differential) system of equations that describe the problem. The abstraction phase (see 6.3) can then be performed after this step.

Based on the parameters determined to be relevant to the problem, dimensioned or dimensionless similarity scales (parameter ratios) are formed in the second step. To accomplish this, the individual parameters are converted to a series of related ratios (scales, proportions). It is important in this case not only to derive scales for the geometric similarity (e.g. the ratio of the length to the diameter of a reinforcement fibre), but also to derive scales of dynamic similarity. Examples include the ratio of the frictional forces to the inertia forces, the ratio of the Young's modulus to the density, or the ratio of two Young's moduli (the matrix and dispersed phases in a composite).

Dimensionless numbers can be formed using a dimensional analysis[13]. In this case, there are standard values describing the technically important ratios and whose use has become so widespread that they are named after actual researchers. This applies especially to the field of heat and material transport (Reynolds number, Nusselt number, etc.). According to Buckingham's pi theorem, it is also possible, using dimensional analysis, to reduce the number of parameters describing the problem by the number of basic variables (basic units) used. This is especially relevant in cases where the number of test parameters shall be reduced to create a manageable test plan. If dimensionless numbers shall be derived from a set of parameters but it is determined in the framework of the dimensional analysis that this is impossible, then either too many, too few, or the wrong factors were determined (the converse is not true).

Full similarity between a biological system and a technical target system in terms of the object to be transferred exists when all ratios specified as relevant are the same in the model and in the target system. This is almost always impossible. It is therefore necessary to consider which ratios are especially important and shall be kept as constant as possible and for which ratios deviations are acceptable.

Examples of important parameters and ratios in the area of biomimetic materials, structures, and components include the following:

— all geometric ratios of a structure;

— mechanical material parameters related to the density;

— force ratios, especially those relating to the force due to weight;

— relative section moduli and form factors.

In the last step, it is necessary to check if the quality criteria used to evaluate the technical target system also apply to the biological system. For example, the quality criteria could require certain maximum or minimum values to be met, but also the minimization of the difference between a given value and a defined target value. If the function of a biological system and a technical target system is to "disperse a powder", then the quality criteria for a poppy head (widest possible dispersion) and a salt shaker (ability to spread salt on an egg) will be very different.

6.3 Abstraction

6.3.1 General

The abstraction process, meaning, the extraction and generalization of the principles found in the biological system, is one of the most important steps but also one of the most difficult steps in a biomimetic project. New knowledge can only be formulated using a general term through abstraction. A prerequisite for abstraction is to separate the important influencing factors from the irrelevant influencing factors for a given effect and then determine the type of relationship that exists between the influencing factors. The validity of the generalization of the results of the abstraction process can be confirmed through observation, analysis, and specific experiments — and in biomimetics, especially on technical prototypes. A particularity of the biomimetic abstraction process is that the formulation of the relationship between the influencing factors and the effects shall be formulated in an interdisciplinary manner. The fact that simplifications are inevitable in many cases when transferring from biology to technology is beneficial to the abstraction process. The results of the biomimetic abstraction process can come in the form of relationships formulated in writing, mathematical models, functional models, function diagrams, circuit diagrams, or construction plans.

6.3.2 Modeling and simulation

6.3.2.1 General

Reality can also be abstracted by creating a model and applying various simulation techniques. At the same time, modelling and simulations offer capabilities for predicting the properties of materials, structures, and components simply and quickly in advance, and therefore, at less expense. For example, it is possible to make predictions of the service life of components based on how materials will respond to mechanical loads. The reduction of development and production costs and the optimization of development processes are often the driving forces behind the use of simulations from the point of view of the industry. One requirement for the profitable use of simulations is a model that has been adapted to the problem to be solved.

Currently available methods allow good descriptions and predictions of the properties of real material systems, but computer-based methods can only describe a portion of reality, and there are still gaps in the understanding of the wide variety of phenomena of complex materials, especially biological materials. This is primarily due to the fact that the time and length scales in which the corresponding material properties are formed, and therefore determine the functionality of the material, span many orders of magnitude. The application of the simulation models at the various time and length scales and the validation of these models is a costly, time-consuming, and complex process. In addition to requiring a further increase in computing power and new analysis methods, this process also requires innovative interdisciplinary strategies in order to connect simulation techniques to experimental material analysis and development.

Biomimetics offers the advantage that there is basically a living prototype available in the form of a biological system that can be used to adapt and validate the technical model. At the same time, it is possible to study structures, especially anisotropic structures and structures spanning multiple scales, and the properties resulting from these structures on biological systems, as well as test modern multi-scale approaches in material simulations.

6.3.2.2 Stress simulation

Most of the studies on biomechanical simulation deal with biological design rules and the development of numerical optimization approaches based on stress-controlled biological growth. In this case, the shapes of components are optimized according to biomimetic principles[1].

6.3.2.3 Material simulation

In addition to the optimization of the shape at a lower hierarchy level, nature also utilizes optimization of the inner structure of the material, for example, using anisotropic and graduated structures such as those found in palm trees and bamboo (and other grasses)[14]. Owing to the hierarchical structure of many biological materials, micromechanical models shall be used at different orders of magnitude for the purpose of simulation in order to describe the structure as completely as possible. Such multi-scale approaches can already be used to obtain good predictions of the elastic properties of bones[15] and wood[16].

The extraordinary strength and toughness of biological materials (for example, mother-of-pearl) can be explained in part by their hierarchical structure. On the other hand, though, the boundary surface mechanics are especially important to their failure behaviour (as is true for all composite materials). Newer approaches, therefore, describe the cohesion of boundary surfaces in biological materials using finite element models of the biological structure that integrate special boundary surface elements (referred to as cohesive elements)[17].

6.4 Material selection

When selecting the materials for biomimetic material and component development, both the material from which the biological system is made, as well as the material that could be used in a possible technical implementation, shall be considered.

Characterization of the biological material is performed during the analysis phase (see 6.1). It is used to determine which influencing factors are relevant to the problem, as well as their relevance to the technical target system (see 6.2).

In contrast to engineering materials, biological materials are generally fibre composite and gradient materials. They have a hierarchical design that ranges from the molecular level up to the level of the overall structure. Biological materials are not homogeneous but are composed of several components with varying proportions. A material is specialized for its function using a suitable design and corresponding composition of the components[18]. For this reason, not only the strengths, but also the deformation and breaking strength can exhibit anisotropic properties. Material is synthesized through growth over the entire lifespan and allows load-based arrangement, as well as corrections, when the situation changes and self-repair in case of partial damage. Biological materials are “intelligent materials” (also referred to as “smart materials”) in the truest sense of the word.

At the end of the abstraction phase, the material properties of the biological system to be reflected in the technical target system are specified. However, they shall not be necessarily integrated into the material of the technical target system, but can also be realized in another manner if necessary (e.g. material stiffness versus structural stiffness). Likewise, other important properties of the technical target system can be realized through a suitable selection of materials even though they were not derived from the material properties of the biological system.

In technical applications, engineers differentiate between constructional or structural materials primarily used to bear mechanical loads and functional materials with special functional properties (in the case of glass, its transparency, for example).

To be able to select suitable materials for technical implementation, it is necessary to know all properties to be realized by the material. Comparing these requirements to the known material characteristics the designer can make a suitable selection, or a new material can be developed if necessary.

A material selection can be optimized according to several criteria using the simplex method, for example. The approach according to Reference [5] in which a property-dependent material index is derived from the various functional requirements placed on the material can also be used as the basis for material selection. A diagram of this procedure for two different material properties can be found in the diagrams from Reference [5] (see 5.2, Figure 2 to Figure 4). Owing to the use of a double-logarithmic scale, the individual material indices appear as straight lines (standards) and make material selection easier.

In addition to the mechanical and functional aspects of material selection, there are also other aspects such as economical aspects (material costs, manufacturing costs) and ecological aspects (recycling and environmentally friendly disposal) that shall be taken into account.

7 Reasons and occasions for using biomimetic materials, structures, and components in companies

From an industrial perspective, there are three dominant arguments that make biomimetics an attractive variant of an innovation process.

— Interdisciplinarity of biomimetics:

The increasing complexity of products and solutions requires new approaches to the innovation process. Qualitative and quantitative optimizations using the classic methods (value analysis, etc.) are usually stretched to their limits today. The interdisciplinary character of biomimetics can provide new impetus in this case. At the same time, innovative products are often based on knowledge from different specialized fields and require convergence of these specialized fields, a fact that is already appearing today in the curricula of numerous modern educational programs. Biology, nanotechnology, and information technology play a key role in this process, and biomimetics can be a major driver of this convergence.

— Biomimetics and sustainability:

Biomimetics can make an important contribution to efficient and consistent (adaptable) solutions in product development. The designs of plants and animals have been tested over unimaginably long periods in innumerable "test series" and exhibit solutions requiring minimal energy and materials[19]. At the same time, the biological systems are optimally embedded in their surrounding systems. The study of the interaction between biological components and an organism or an organism and the ecosystem, therefore, offers an important foundation for controlling the environmental impact of a technical product or process.

— Higher marketing value of biomimetic developments:

Biomimetics offers extraordinary starting points, based on the biological system, not only for explaining the pure function, but also for explaining the entire process up to the realization of the product and tapping into our innate interest in nature (storytelling).

Annex A
(informative)

Examples of biomimetic materials, structures, and components

A.1 General

The biomimetic features transferred from a biological system to a technical material or component can range from its molecular structure to its macroscopic shape.

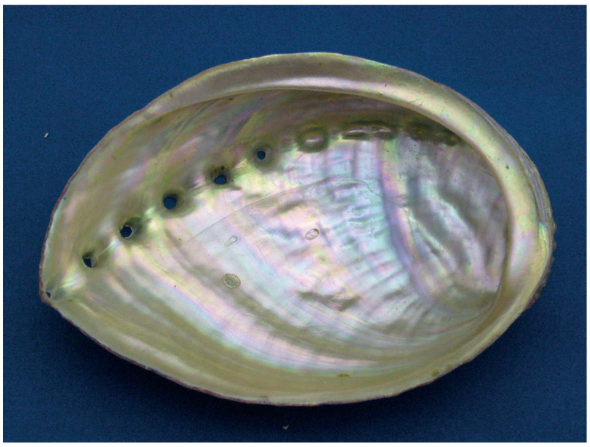
A.2 Biologically inspired polymers

Material design at the molecular level is demonstrated outstandingly by some biological polymers. Examples include natural rubber made from the sap of the *Hevea brasiliensis* and its cultivated strains, as well as the resilin in the ligaments of the flea and the grasshopper. Their highly elastic properties with simultaneously high mechanical load capacity by far exceed the performance of most synthetic polymer materials. Since it has become possible in individual cases to clarify the relationship between the desired properties and the underlying molecular architecture and model using synthetic methods, it is possible to manufacture plastics with new properties from petrochemically manufactured raw materials. On the one hand, success was achieved using new types of catalysts and on the other hand, using suitable starting molecules (monomers). As a result of this, it is possible to control the stereoregularity, create blocks of molecules and/or branches, and control the molecular weight distribution. In spite of their initial success, these methods have only started to reach their full potential, and some aspects are already highly reminiscent of the precision and variability of biological growth processes. Only the future can tell if the extent to which an especially high performance polymer structure will be inspired by a specific biological system, or if it is more likely that the functional bandwidth, which is achieved in nature by derivatization of a few basic molecules, will become an overall inspiration for macromolecular chemistry.

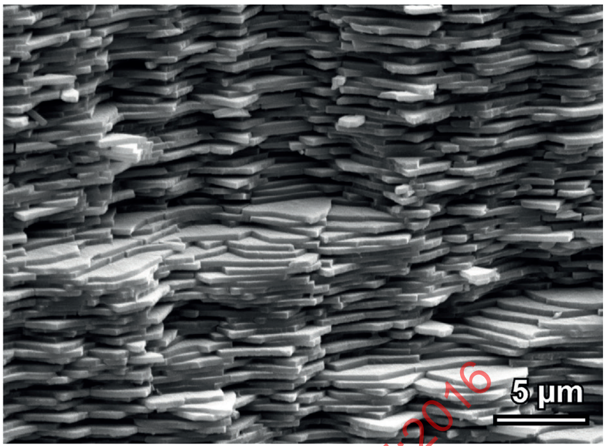
A.3 Biomimetic nanostructures and microstructures, mother-of-pearl analogy

In many cases, biological materials that perform especially well consist of “hard” and “soft” modules (bones, teeth, mussel shells, silica skeletons, magnetic nanoparticles arranged in chains, for example, in magnetotactic bacteria). The material composition plays a less important role in this case than the nanostructural and microstructural design and the corresponding hierarchies and anisotropies of the hybrid material. Such designs allow the biological material to reach a good level of fracture toughness while simultaneously providing high strength and stiffness.

A much-discussed model for biomimetic material is mother-of-pearl, the material in mussel shells, which consists of calcium carbonate (aragonite) and proteins. In spite of its very low portion of organic material, mother-of-pearl has a significantly higher breaking elongation in comparison to technical ceramic materials. In this case, nature surpasses the tensile strength of silica ceramics and polymer-layered silicate nanocomposites using a more or less “poor” construction material, calcium carbonate, while simultaneously achieving a high stiffness (comparable to that of ceramic; see Table A.1). This is accomplished using mother-of-pearl in a construction similar to that of a brick wall; see Figure A.1 b).



a) Image of an abalone



b) Layered structure of mother-of-pearl

Figure A.1 — Abalone and mother-of-pearl

Table A.1 — Comparison of the mechanical properties of mother-of-pearl, silica ceramic, and a polymer nanocomposite, according to References [20] and [21]

	Stiffness (tensile modulus)	Tensile strength	Breaking elongation	Organic portion
	GPa	MPa	%	%
Mother-of-pearl	40 to 70	80 to 135	1	<2
Silica ceramic	50 to 80	25 to 40	<0,1	0
Organoclay/PA6 nano-composite	2,5	80	15 to 25	>95

From studies of mother-of-pearl, it can be determined that polymers which are able to interact with mineral phases are especially important for the production of composite materials in which they function as an "adhesive" for the dispersed mineral phase. This was shown in studies of the manufacture of biomimetic mother-of-pearl analogs. One mother-of-pearl analog, for example, was manufactured through sequential deposition using charged layer silicates and oppositely charged polymers. This analog had mechanical properties matching or even accomplished in mother-of-pearl using a construction[22]. In this case, surface-modified montmorillonite layer silicates were deposited with polycations (pDADMAC) and then linked to the remaining free ionic groups with polyvalent anions. It was possible to manufacture flexible, semi-transparent films with a thickness of approximately 30 µm whose mechanical properties matched those of natural mother-of-pearl. Owing to the ionic interactions, these materials also possess self-healing properties[20].

A.4 Pearlescent and interference pigment

An important group of biomimetic products at the microscale are so-called pearlescent and interference pigments. Even though the term "biomimetics" was not used in early papers on their development and manufacture, they all referred to analogies to biology and then specified the objectives for the technical analog based on them. A biological system for pearlescent pigments can be found in mother-of-pearl, but especially in the platelet-shaped crystallized guanine crystals found in the scales of fish, like herring, sardines, and bleaks. The guanine crystals are 20 µm to 50 µm long, 1 µm to 10 µm wide, and have a thickness of only 25 nm to 75 nm. They have an index of refraction of about 1,8, and their special glossy effect is the result of the platelet shape, their good reflection properties while being transparent at the same time, and their extreme thinness.

The extraction of guanine from fish scales is technically complex and expensive. For these reasons, scientists initially tried to manufacture guanine synthetically, but with no success. They then tried to make platelet-shaped crystals from other materials. In this case, though, it was difficult to control the crystal growth to obtain the desired shape, and the materials with which this was possible were often toxic to humans and the environment (lead carbonates) or exhibit other weaknesses when applied (bismuth oxychloride). Modern pearlescent pigments are based primarily on mica platelets coated with titanium dioxide. Natural mica serve as an ideal, transparent substrate with an atomically smooth surface. The thicknesses of the titanium dioxide layers on the mica substrate range up to 200 nm. Depending on the thickness, glossiness and interference effects will appear. The mica platelets, like biological guanine, have a very high aspect ratio that facilitates their plane parallel arrangement on the component surface. Pearlescent pigments are used especially in lacquers and cosmetics where they create glossy and colour-changing effects.

A.5 Self-sharpening tools

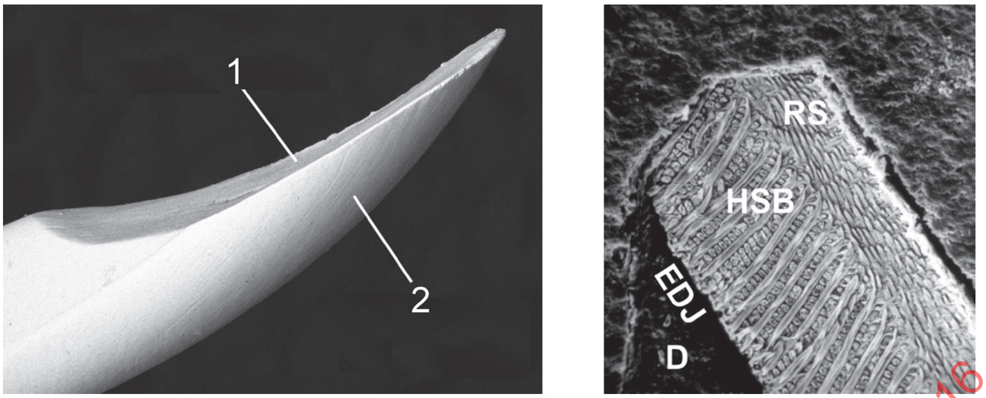
An example of biomimetic materials and structures spanning the micro and macro levels are self-sharpening cutting tools. The teeth of rodents have become extremely efficient self-sharpening cutting tools over the course of evolution. The front sides of the incisors of rodents have less enamel than on 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.2 a).

In addition to these basic structures, the microstructure of the tooth, in particular, plays a central role in the functionality of this cutting system. The enamel consists of radial enamel, which allows forces to be transmitted efficiently and provides low friction on the top side. To redirect forces to the base body and prevent long cracks from forming in the enamel/dentine layer, there is a layer underneath it consisting of the so-called Hunter-Schreger bands.

The primary challenges in the development of self-sharpening knifes include the knowledge of the tribological processes between the material cut and the cutting tools needed, as well as their specific manipulation, and the avoidance of cracks and flaking on the exposed side of the hard layer[2][23].

However, the abstracted knowledge already forms the basis for transfers into technology. It was possible to develop self-sharpening machine knives for application in strand cutting of mineral-filled plastics (e.g. Rodentics®[1)]).

1) Rodentics® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.



a) Reduced enamel layer on the front of the tooth

b) Microstructure of the enamel

Key

1 soft cutting face
2 hard free surface
RE radial enamel
HSB Hunter-Schreger bands
EDJ enamel/dentine joining layer
D dentine

Figure A.2 — Structure of the tooth of the vole

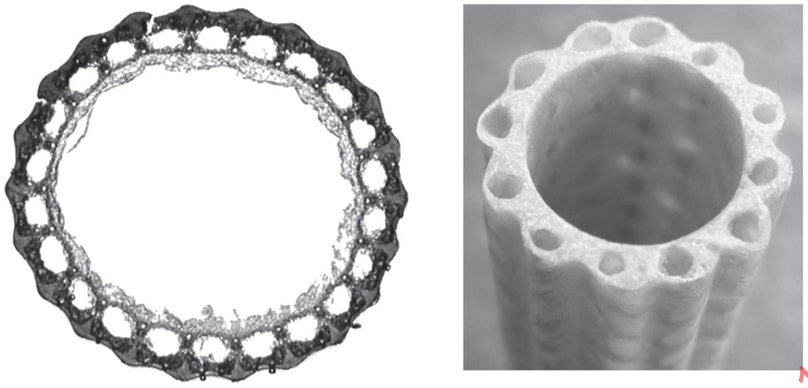
A.6 Technical plant stem

Several of nature's construction principles were transferred to the "technical plant stem". It is another example of the transfer of biological structures at the microscale (fibre orientation) and macroscale (design of the cross-section). This process led to a completely new biomimetic product that never existed in this form before in nature or in technology; see Figure A.3 b).

The biological systems include the giant reed (*Arundo donax*), woody grasses, and winter horsetail (*Equisetum hyemale*). With their hollow stalks and thin stem walls, they are amazingly stable and lightweight constructions with extraordinarily good vibration dampening properties. The central stems of plants are fibre composite materials that do not delaminate even when exposed to dynamic wind loads. The stability of the fibre and tissue composites is increased by gradual transitions. Plants have excellent material properties due to this composite design, as well as due to the optimization of fibre distributions and fibre orientation according to the stresses arising in the stem. For technical fibre composite materials, knowledge of the structure and function of composite materials found in plants is of great interest.

The giant reed is characterized by a complex fibre composite structure with a high specific stiffness and strength. The reasons for this are the optimized fibre arrangement, the gradual shift to wood in the base tissue with gradual changes to the cell/cell wall ratio, as well as the gradual stiffness transition between the stiff fibres and the less stiff base tissue matrix. In addition to very good dampening of mechanical vibrations, the giant reed is also characterized by "ample breaking strength" with several pre-failure events. This is a behaviour that is also desirable for fibre composite technology because fibre composite materials generally react with a brittle breaking strength, which then significantly reduces the possible areas of application of this lightweight material.

An extraordinarily efficient example of a lightweight design in plants is winter horsetail; see Figure A.3 a). It is easy to see the sandwiched construction of the cross-section: A thin outer mantle made of non-lignified strengthening tissue and a double inner ring made of cells with partially lignified cell walls are separated by large hollow spaces due to wedge-shaped strengthening structures between these spaces. These stabilizing elements are reminiscent of T-beams. This sandwiched design is a lightweight construction with high specific flexural strength and buckling stability that uses the least amount of material possible[24][25].



a) Cross section of the stem of the winter horsetail

b) Technical plant stem

Figure A.3 — Cross section of the stem of the winter horsetail and technical plant stem

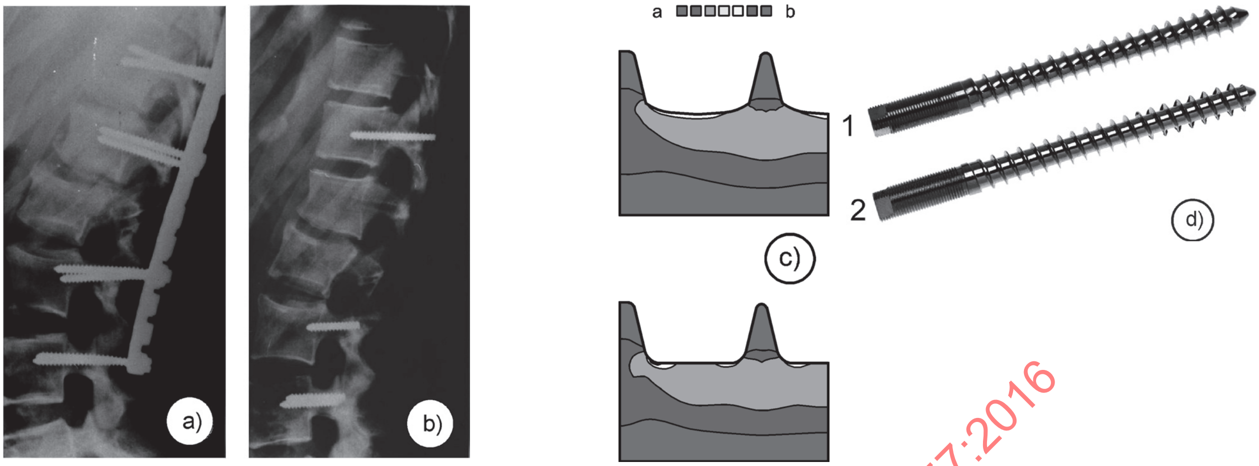
A.7 Orthopaedic screw

In addition to the material properties and the load, the macroscopic design is also a very important factor in the lifespan and failure of biological structures and technical components[26]. Biological structures, therefore, can adapt their design through load-adaptive growth when subjected to a mechanical load according to the "axiom of constant stress"[27]. According to this axiom, an equal distribution of the stress on the component surface is achieved through growth at highly loaded areas and optionally through shrinkage at underloaded areas. The component as a whole is capable of bearing a higher load and its lifespan is increased as a result. This has been implemented technically in the CAO (computer aided optimization) method. To accomplish this, the load-adaptive growth like that of the natural model, the tree, is simulated on a computer with the help of special software for stress analysis of components so that the mechanical stresses can be homogenized and reduced during the design phase.

Figure A.4 a) shows a treated spine. Its damaged section is supported and relieved of load by placing a plate over it. To fasten the implant in place, orthopaedic screws (pedicle screws) are inserted in the vertebral arch. The load is transferred by the screws from the bone into the implant and vice-versa. Figure A.4 b) shows fragments of pedicle screws. This failure could not be avoided by using larger screws (due to anatomical conditions) or by using a better material (due to biocompatibility requirements).

One cause of the breakage was found in the design of the thread root of the screw. Mechanically speaking, the thread of a screw is a helically wound annular notch. The non-optimized design was rounded off using arcs in the thread root, which cause high notch stresses to arise. By optimizing the shape with the CAO method, the notch stress was eliminated after just a few growth phases. The optimized shape of the thread of the pedicle screw is practically without notch stress; see Figure A.4 c).

Experimental verification in flexural fatigue tests showed that the optimized screw did not exhibit any visible crack formation even though it had a lifespan of 20 times more load cycles than the non-optimized screw; see Figure A.4 d). The danger of the implant breaking is reduced to a minimum through optimization based on principles of biological growth.



a) X-ray image of a human spine with implant

b) Fragments of broken pedicle screws

c) Comparison of the stress analyses on the model of a CAO optimized screw and a conventional screw with help of the finite element method

d) Comparison of a CAO optimized pedicle screw and a conventional pedicle screw. Load cycles determined in experiments using flexural fatigue testing

Key

1 optimized screw: no failure after 5 000 000 load cycles

2 conventional screw: failure after 220 000 load cycles

a Low stress.

b High stress.

Figure A.4 — Orthopaedic screw

A.8 Biomimetic manufacturing techniques for materials and components

In many cases, a biomimetic material or component is manufactured using conventional manufacturing techniques. These techniques include casting, extrusion, and laminating techniques, a wide variety machining and joining techniques, as well as sintering techniques. In these top-down technologies, the final form of the component is manufactured from a largely homogeneous material or a flowable preliminary form is poured into a mould where it hardens.

If materials and components are to be manufactured to have an internal structure and composition that has been locally optimized to meet the requirements of the particular application, then new manufacturing techniques applying the bottom-up principle are necessary. These manufacturing techniques shall be able to partially or completely model aspects of biological growth, such as cell division, growth, differentiation, and specialization, as well as the formation of functional units (organs) and complete organisms including their genetic controls. The special challenge in this case is to manufacture across a range of scales, ideally starting at the molecular level, that integrates several hierarchy levels and aggregates to a complex overall system.

Important bottom-up methods that have become established methods for the most part include the generative manufacturing process (previously referred to as rapid prototyping or rapid manufacturing). In contrast to moulding, casting, or subtractive manufacturing processes (cutting), the efficiency of generative manufacturing process is less affected as the piece count decreases, the individualization of production increases, and the complexity of the component geometry increases. Due to the layer-by-layer manufacturing technique, it is possible to construct objects by starting small and increasing the scale, just like in nature, which significantly raises the potential for the development of new types of materials and components with locally varying compositions and properties.

The refinement of conventional methods can also lead to manufacturing techniques having an especially great potential for manufacturing biomimetic components. Fibre composite materials, for which a wide variety of biological systems can be found, especially in plants, are used in technology and especially in the transportation industry where high stiffness and strength and low weight is required. The pultrusion technique is especially suited for the manufacture of endless fibre composite profiles in one step. This technique can also be used to process duroplastic and thermoplastic matrices. If a braiding machine is integrated, then the process is referred to as the braiding pultrusion technique (see Figure A.5). With the braiding technique, it is possible to introduce helical fibres into the structure so that the profiles are also very well suited to handle torsional forces. This technique is used to manufacture technical plant stems[24].

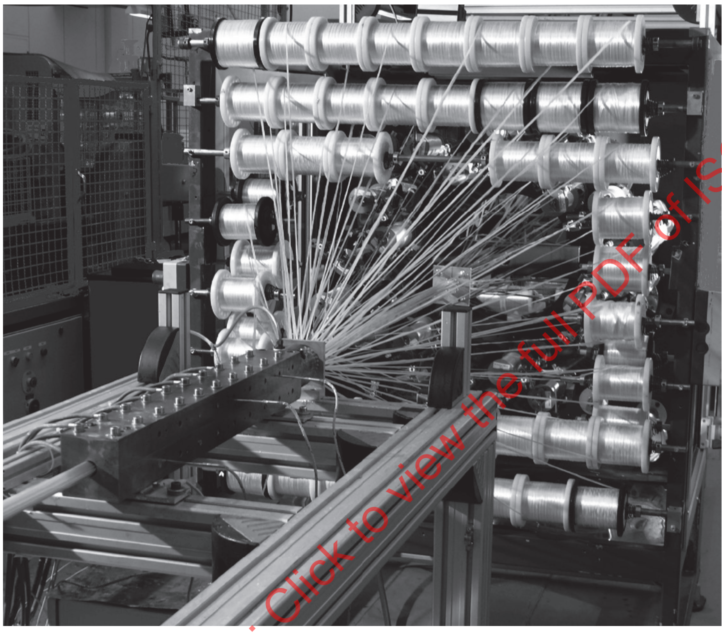
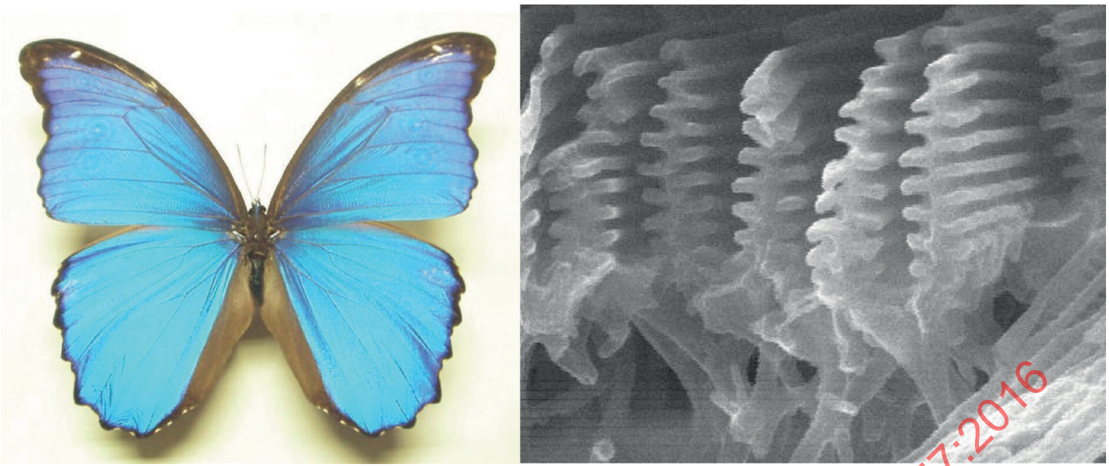


Figure A.5 — Braiding pultrusion technique

A.9 Structural colour

Morpho butterflies have wings coloured in vibrant cobalt-blue; see Figure A.6 a). These colours are known to be caused by structural coloration. The Morpho's wings have lamellate structure which shows optical interference effects; see Figure A.6 b). The lamellate structure of their wing scales has been studied as a model in the development of biomimetic fabrics. Morphotex®2) is the world's first optical colouring fibre, inspired by the structural coloration of Morpho butterflies[29]. From the abstraction of the mechanism of structural colour, optical interference colours were created by stacking two polymers having different refractive indices. This fibre comprises 61 polyester and nylon in alternating layers in which controlled thickness is from 70 nm to 100 nm, because the optical index difference between polyester and nylon is 0,5. Although no dyes or pigments are used, four types of basic colours such as red, green, blue, and violet are created based on the precisely controlling thickness and structure of fibres (see Figure A.7). The fibre has various applications in a wide range of fields, not limited to fabric or knitting, but reaching those of painting, and cosmetics.

2) Morphotex® is the trademark of a product supplied by Teijin Fibers Limited. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.



a) Morpho butterfly   b) Lamellate structure of the wing scales

Figure A.6 — Morpho butterfly and lamellate structure of the wing scales[28]

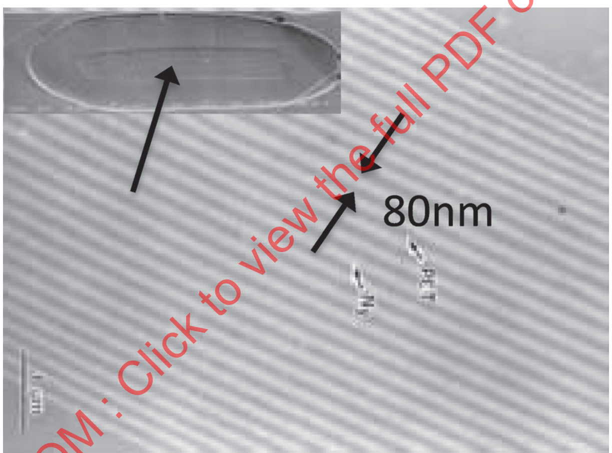


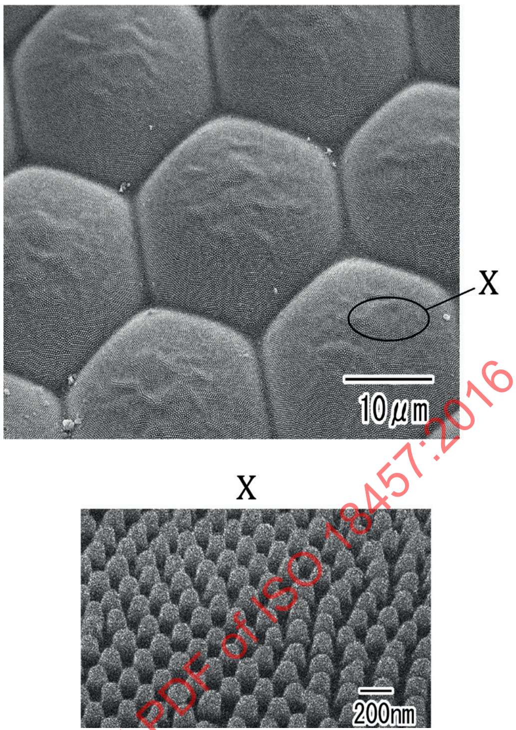
Figure A.7 — Cross section of technical structural colour[30]

A.10 Anti-reflection structures

The anti-reflection structures currently in use are produced by a combination of layers with high and low indices of refraction. The refinement of layered systems leads to the development of the most well-known example of periodic nanostructures, the moth-eye effect (see Figure A.8). Moth-eyes have periodic nanostructures that show low reflection[32]. The effect of these structures is due to a continuous change of the index of refraction between air and substrates. Such structures are technically interesting in terms of cost reduction aspects, for example. Instead of needing several coating steps, this layer can be realized in a single moulding step. Recently, research and development for the industrial production of the moth-eye structures for anti-reflection has been advanced (see Figure A.8). Mould manufacturing is one of the most essential technologies in these approaches[33].

In the ideal case, the structuring step can be combined with the manufacturing process of the component.

a) Moth



b) Moth-eye structures

Figure A.8 — Moth and moth-eye structures[31]

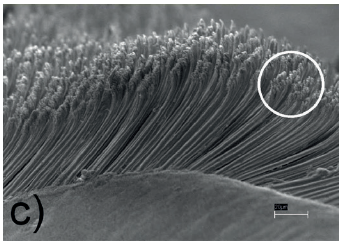
A.11 Adhesive tape

A biomimetic reversible adhesive tape is an example of biomimetic development by biology push. The excellent adhesion/detachment qualities of the gecko foot have attracted particular attention recently. It is possible for the gecko to stick perfectly to a surface without the need for a secretory substance corresponding to an adhesive and to move in three dimensions, even on flat surfaces, such as window glass, where nails are ineffective (see Figure A.9). The adhesive force is thought to be controlled by an intermolecular force (Van der Waals force) that occurs between the gecko foot and the target surface[35]. Since the adhesion energy when the Van der Waals force works between two flat surfaces in contact is inversely proportional to the square of the separation, the way in which the surfaces are made to approach each other is important.

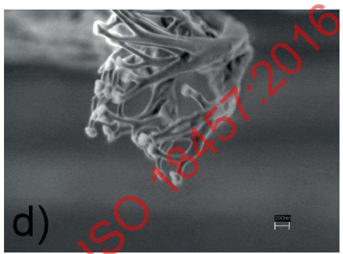
Many researchers have developed surfaces with synthetic setae based on the principles of gecko footpads, allowing the design principles and mechanical/adhesion properties to be studied (see Figure A.10). However, most manufacturing methods are expensive, making it difficult to produce a large surface area.

a) Gecko adhered on a plastic plate

b) Gecko's foot



c) Hairy structure on the finger

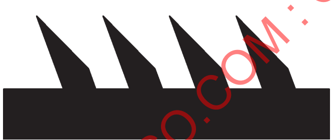


d) Spatular tips of a single gecko seta

Figure A.9 — Adhesion and detachment qualities of the gecko foot[34]

a) Column type

b) Mushroom type



c) Slant type

d) Hierarchical structure

Figure A.10 — Various technical hairy structures[34]

A.12 Innovation process for the manufacture of self-cleaning plastic parts

The innovation process for the manufacture of self-cleaning plastic parts is an example of an industrial application of biomimetics. To open up new markets, products that are both beneficial to customers and have acceptable manufacturing costs are needed, but especially that have "unique features", i.e. features that the competition does not offer. A chemical corporation was searching for an innovative way to increase the value of its technical plastics portfolio, and for this reason, a group of developers approached biologists. Their intention was to transfer a property found in a biological material to products produced synthetically with methods used in the plastics processing industry. Biologists have observed that the surfaces of certain plants, notably the leaves of the lotus plant, always appear to be clean. To explain this phenomenon, it was suggested that the surfaces of lotus leaves are self-cleaning. Particles of dust and spores from harmful organisms deposited accidentally, or deliberately, are absorbed by water droplets from rain. Due to the strong water repellency of the lotus leaves, these droplets roll off easily, carrying contaminants with them. Analysis revealed that the self-

