VDI Zentrum Ressourceneffizienz

VDI ZRE Publications: Brief analysis No. 19

Resource efficiency through biomimetics


September 2017

VDI ZRE Brief analysis No. 19: Resource efficiency through biomimetics

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We would like to thank Prof. Dr. rer. nat. Antonia Kesel, head of the degree course Bionic at the Hochschule Bremen - University of Applied Sciences and chairwoman of the VDI advisory board Bionic, for her professional support.

The brief analysis was prepared within the framework of the National Climate Protection Initiative of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

The brief analyses of VDI ZRE provide an overview of current developments related to resource efficiency in research and industrial practice. They each contain a compilation of relevant research results, new technologies and processes as well as examples of good practice. The brief analyses thus provide a broad audience from business, research and administration with an introduction to selected areas of resource efficiency.

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Printed on environmentally friendly recycled paper.

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LIST OF ABBREVIATIONS

ALM	Additive layer manufacturing
BIOKON	Registered Association of Biomimetics Network of Excellence
BIONA	Biomimetic Innovations for Sustainable Products and Technologies
BMBF	Federal Ministry of Education and Research
BMUB	Federal Ministry for the Environment, Nature Conservation, Construction and Nuclear Safety
BROMMI	Biomimetic Arm Kinematics for Robotic Applications in Safe Human-Machine Interaction
CAD	Computer-aided design
CAIO	Computer-aided internal optimisation
CAO	Computer-aided optimisation
CFD	Computational fluid dynamics
DBU	German Federal Environmental Foundation
DFG	German Research Foundation
DIN	German Institute for Standardisation
EA	Evolutionary algorithms
ELiSE	Evolutionary Light Structure Engineering
FEM	Finite element method
HGF	Helmholtz Association of German Research Centres
IKTS	Fraunhofer Institute for Ceramic Technologies and Systems
IPT	Fraunhofer Institute for Production Technology

ISO	International Organisation for Standardisation
IS	Fraunhofer Institute for Surface Engineering and Thin Films
ITV	Institute of Textile Technology and Process Engineering Denkendorf
KIT	Karlsruhe Institute of Technology
SMEs	Small and medium-sized enterprises
PROSA	Product Sustainability Assessment
S2C	Sweep-spread carrier
SKO	Soft kill option
TAK	Tripedal alternate cascade
TBTH	Tributyltin hydride
UMSICHT	Fraunhofer Institute for Environmental, Safety and Energy Technology
VDI	Association of German Engineers
VDI ZRE	VDI Zentrum Ressourceneffizienz GmbH

PART 1: BRIEF ANALYSIS

1 INTRODUCTION

Biomimetics combines biology and technology in an interdisciplinary collaboration. It is an interdisciplinary field that is not limited to a research or industrial sector. The aim of biomimetics is to solve technical problems by abstraction, transfer and application of knowledge gained from biological models. Their application in the product development process as innovation method enables innovative technical solutions. These can give companies **competitive advantages**.

Biomimetics offers considerable potential with regard to **resource efficiency**. It is believed that a so-called "ecological management" is possible by transferring biological models and principles into technology.[1] This assumption is justified by the fact that nature, for example, usually uses energy and material purposefully and efficiently. The functions and properties developed throughout the course of evolution are thus "ecologically" optimised.

However, it must be taken into account that this optimisation has taken place as a result of the adaptation of organisms and systems to the influencing variables of the environment and to the generation intervals of the organisms. In the course of evolution, populations adapt to changing environments, primarily for the conservation of the species and not for the optimisation of single individuals. Thus, the mechanisms of evolution differ from the prerequisites of industrial production.

Nonetheless, the following biological strategies can be used to derive successful resource efficiency strategies for the product development and the production process:[2]

- Close natural cycles – almost every organic material is recycled or reused.
- Efficient use of materials – material is used where it is needed and broken down where it is redundant.
- Constructions are adjusted according to the predetermined service life.

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[1] Cf. von Gleich, A., Pade, C, Petschow, U. and Pissarski, E. (2007).

[2] Cf. VDI 6220 Part 1: 2012-12, p. 19 et seqq.

- Materials are produced in a resource-conserving manner in a mild environment (low pressure, neutral pH, low temperature).
- For a hierarchical structure, only a few materials are used, which often integrate different functions. Often they are adaptive, redundant and fault-tolerant, and they still have the ability to self-repair.
- Adjustments to changing environmental conditions take place during ongoing operations; organisms cannot "close due to reconstruction".

The market has already established a large number of biomimetic **products**. In the development of new or optimised biomimetic products are usually functional and economic goals, such as innovative functions, weight reduction, space savings or noise protection in the focus of companies. Nevertheless, resource efficiency potentials are recognisable in many products. For example, the resource efficiency of lightweight products is addressed directly: Here, **biomimetic methods** achieve both weight and material savings. In addition, biomimetic methods are also used today in many other sectors as a solution strategy for technical issues in product development, without making a specific reference to this association. As a result, significantly more companies are already using biomimetics today than is known to the public. However, to date, no comprehensive assessment of resource efficiency through biomimetics or a consistent assessment of biomimetic solutions has been carried out in terms of resource efficiency.

The scientific discipline of biomimetics uses diverse *structures and functional principles* **of biological models** as inspiration for technical developments. Nature's models offer great innovation potential and are therefore attractive for companies. They have adapted optimally to their respective habitat and environmental conditions over a long period of development. The prerequisite for decoding the corresponding functional principles and the development of biomimetic innovations is basic biological research. Nevertheless, due to the complex approach of drawing inspiration from nature and the great variety of biological models and how they function, it is not always easy to derive technical solutions.

The aim of this brief analysis is to **qualitatively evaluate current examples from biomimetics in terms of resource efficiency** and thereby demonstrate the contribution they can make to material and energy efficiency. It is intended to clarify at which point in the product life cycle or the product development process the greatest resource efficiency potentials can be expected from biomimetic solutions. The brief analysis is intended to give information and assistance to the relevant stakeholders in companies that want to use biomimetics as an **additional method in product development or optimisation and process optimisation**.

The research and development landscape in biomimetics is developing rapidly, so this brief analysis can only represent a selected overview of current product examples and research projects.

2 BIOMIMETICS AND RESOURCE EFFICIENCY

2.1 What is biomimetics?

Biomimetics – learning from nature – is based on biology and provides inspiration for solution ideas or strategies for the development of technical innovations. It is about recognising the design methods and functional principles of biological models. Biomimetics means that new technical solutions are created through detailed investigations of biological models and the consistent transfer of biological functional principles.[3]

The basis for biomimetics is biodiversity: Inspirations from nature, i.e. from living organisms and biological systems, are available in an immeasurable number and variety. It is estimated that there are 10 to 20 million animal and plant species worldwide, of which only a small fraction is known and described. Without these biological models, the development of biomimetic products and methods is not feasible. Here, the possibilities are far from exhausted, and many functional principles are still unknown.[4]

For more than 50 years, scientists have been using the term biomimetics to research natural phenomena and to develop innovative products from them. But only since 2001 have these activities gained new momentum in Germany. In that year, the Federal Ministry of Education and Research (BMBF) began to promote biomimetics with the establishment of the biomimetics competence network BIOKON Forschungsgemeinschaft Bionik-Kompetenznetz e.V. This measure culminated in a funding concept for biomimetics, in the course of which application-oriented research was supported by joint projects from universities with industry participation until 2012. [5,6] One focus of the projects in the last funding measure BIONA (Biomimetic Innovations for Sustainable Products and Technologies) was on sustainability.

[3] Cf. Jessel, B., Tschimpke, O. and Walser, M. (2009), p. 20 et seqq.

[4] Cf. Jessel, B., Tschimpke, O. and Walser, M. (2009), p. 9 and pp. 33 - 53.

[5] Cf. Federal Ministry of Education and Research (2005).

[6] Cf. Federal Ministry of Education and Research (2011b).

BIONA was also associated with resource efficiency through its research on sustainability.

A large number of publications on biomimetic developments have been published in which the examples of biomimetic products known today, such as lotus effect®, artificial shark skin, touch fastener Gecko Tape® and many other examples, are described in detail. A few selected publications are mentioned here as examples.[7, 8, 9]

Biomimetic research and product development take place in almost all research areas and industrial sectors. Here, **natural functional principles** such as structured surfaces or biological growth processes are used across all industries. On the other hand, however, a complex industrial end product such as the automobile may consist of various biomimetic components, e.g. a car body with a biomimetic shape, biomimetic lightweight components, surfaces, tyres and backrests.[10] In order to create a classification system despite this diversity of application potentials, biomimetic applications are usually divided into specialised areas such as surfaces, robotics, sensor technology, architecture, biomimetic optimisation and so on. This classification corresponds to both the VDI Guideline Series (Table 4 on page 77) and the specialist groups of BIOKON.[11] Even though this classification addresses different systematic levels, and there are a variety of overlaps, it has become established and proven itself in everyday work. The variety of research directions and industrial applications means that scientists and engineers of various disciplines can be involved in biomimetic development work.

In the last 20 years, technologies such as imaging and simulation techniques, nanoscale detection and production methods, and additive processes have rapidly evolved, opening up new opportunities for biomimetics. **Biological structures are hierarchical and, in most cases, multifunctional.** Precise measurements, simulations and design methods in the small-scale range became possible only with the further development of these technologies. By

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7 Cf. Luther, W., Beismann, H. and Seitz, H. (2011).
8 Cf. Speck, T., Speck, O., Neinhuis, C. and Bargel, H. (2012).
9 Cf. Nachtigall, W. and Wisser, A. (2013).
10 Cf. Seitz, H. (2013), p. 12.
11 Cf. BIOKON (2017).

now, various methods are available for functional formation of analogy, the analysis of functional principles and modes of action as well as the production of biomimetic prototypes and solutions. In addition, for example, very slow or very fast biological processes can be studied with the help of high-resolution cameras and computer evaluations.[12] This also applies to the analysis of surfaces that have their functionalities due to their nano-structuring. Even here, the analysis and simulation methods have evolved rapidly. This includes various numerical simulation methods such as finite element method (FEM), computer-aided design (CAD) and computational fluid dynamics (CFD). These computer-aided techniques have evolved significantly in recent years, thus greatly reducing development times. The design of complex hierarchical constructions became easier through the further development of the additive procedures. Embedding several functionalities in one structure also became a possibility. It is assumed that additive methods, in particular, also offer further development possibilities through the use of the numerical simulation methods of biomimetics.[13]

Definition of biomimetics

In the past, there has been a great deal of discussion at the national and the international level about how exactly biomimetics is to be defined, and what exactly it means when a product is identified as biomimetic. In order to give science and businesses a guideline and a common language, the Association of German Engineers e. V. (VDI) developed a series of VDI guidelines (Table 4). Guideline VDI 6220 Part 1 describes the basics of biomimetics and defines the essential terms: **"Biomimetics combines biology and technology in an interdisciplinary collaboration with the aim of solving technical problems through the abstraction, transfer and application of knowledge gained from biological models."**[14] According to this definition, biological models can be biological processes, materials, structures, functions, organisms, principles of success and the process of evolution.

[12] Cf. Poppinga, S. and Speck, T. (2016), p. 9.
[13] Cf. Handelsblatt (2016).
[14] VDI 6220 Part 1: 2012-12, p. 9.

The VDI's definition has largely been adopted at the international level in the standard DIN[15] ISO[16] 18458. In addition, however, a clear distinction is made between biomimetics and bionics. Bionics is defined as a "technical discipline that wants to reproduce, improve or replace biological functions by their electronic and/or mechanical equivalents"[17]. Thus, bionics is more concerned with the area of robotics and automation technology.

The German word "Bionik" is generally translated in English as "biomimetics". However, in recent years, regardless of the definitions set forth by ISO and VDI, the word "bionics" is increasingly used as an English translation. Other terms such as bio-inspired, biomimicry and biomimesis are also used synonymously for the word "Bionik".[18]

In this brief analysis, biomimetic solutions are divided into biomimetic products and biomimetic methods:

Biomimetic product: An intermediate product, end product or tool that is based on a biological model. After abstraction and technical implementation, it is used in a production process, as a component or put on the market as an end product.

Biomimetic method: Method developed in a process of the biomimetic work (computer-aided optimisation (CAO), computer-aided internal optimisation (CAIO), soft kill option (SKO), evolutionary algorithms (EA), evolutionary light structure engineering (ELiSE), biomimetic thinking tools). The methods can be applied in a product development process without the need for an additional biomimetic development. The result of using a biomimetic method is a biomimetic product. EA is the exception as the result of an optimisation with EA can usually no longer be assigned to a biological model.

[15] DIN – German Institute for Standardisation
[16] ISO – International Organisation for Standardisation
[17] DIN ISO 18458: 2016-08, p. 8
[18] Cf. VDI 6220 Part 1: 2012-12, p. 10.

Criteria for biomimetic solutions

Guideline VDI 6220 Part 1 and DIN ISO Standard 18458 stipulate that natural and technical parallel developments are not biomimetics. An example of this is the Munich Olympic roof, which was developed in analogy to spider webs. Here there was no transfer of biologically active principles into the technology. Again and again, technical products are developed that are similar in their shape to biological models and perform similar tasks. Although these developments use biological models, they cannot be described as biomimetic developments (Chapter 3.4).

In order to achieve a common understanding of the distinction between biomimetic and non-biomimetic solutions **three criteria** have been defined. A biomimetic solution must therefore go through three steps:[19, 20]

(1) the performance of a functional analysis of the biological system,

(2) the abstraction of the biological system into a model and

(3) the transfer and application of the model for the development of a technical product.

Using the example of the biomimetic shark skin for ship hulls, this means:

(1) **Analysis**: The surface of the shark skin has been studied in terms of its structure, flow characteristics and behaviour in the flow. On the skin are movable placoid scales that show grooves in the flow direction, this is the so-called riblet structure. The flexible scales and their riblet structure are responsible for giving the shark favourable flow characteristics and that no sea creatures (e.g. barnacles) can adhere.

(2) **Abstraction**: The analysis showed that a pliable, rough surface of the shark skin (mobile placoid scales) prevents the attachment of marine life, such as barnacles. A grooved structure (riblet structure) of the skin scales ensures that frictional resistance is reduced. The surface properties “flexibility”, “mobility”, “pliability” and “groove structure” thus

[19] Cf. DIN ISO 18458: 2016-08, p. 12.
[20] Cf. VDI 6220 Blatt 1: 2012-12, p. 12 et seqq.

have a significant influence on the flow behaviour and antifouling. They are the analogy model, which can be generalised by further abstraction steps (e.g. derivation of the properties and functions into theoretical mathematical formulations). The model is the basis for a transfer into a technical system.

(3) **Transfer**: Initially, a **plastic film** was produced with grooves, which was first glued to aircraft fuselages. Later, a **paint/varnish** was developed, whose surface structure is formed independently when applied to the ship hull. Although this self-structured surface is not groove-shaped, it basically prevents sea-creatures from adhering.

If one of these three criteria is not fulfilled, strictly speaking – in accordance with guideline VDI 6220 Part 1 and DIN ISO Standard 18458 – it is not possible to call it a biomimetic product. In both publications, examples are tabulated, which illustrate when a product is biomimetic and when not.[21, 22]

Aspects of sustainability

Due to the many efficient solutions from living nature such as opportunism, i.e. the use of existing resources, circular economy, cascade use, multi-functionality, solar economies and efficiency adjustments, many scientists suspect that biomimetics is not only a promising innovation method, but also holds the potential of a so-called more ecological or sustainable technology.[23] An assessment of sustainability with quantifiable indicators is necessary in order to test this.

The aim of an accompanying measure within the framework of the BIONA funding measure was to evaluate the technical solutions of all funded joint projects and junior research groups with regard to their contribution to sustainability.[24] For this purpose, a methodology was used that was already developed in 2001 as an integrative approach by the Helmholtz Association of

[21] Cf. VDI 6220 Part 1: 2012-12, p. 13.
[22] Cf. DIN ISO 18458: 2016-08, p. 13.
[23] Cf. Bertling, J. (2014), p. 186 et seqq.
[24] Cf. BIONA (2012).

German Research Centres (HGF) on sustainability. Against the background of inter- and intragenerative justice, three general, cross-dimensional sustainability goals were defined (Table 1). For the implementation of systematic sustainability analyses, the HGF's approach stipulates that the above-mentioned goals must be substantiated by indicator systems that are tailored to the respective subjects under observation.[25]

In the accompanying measure of the BIONA measure, a total of 15 indicators for the evaluation of biomimetic solutions were derived (Table 1).[26] Each of these indicators can be operationalised so that a quantitative assessment is possible. So far, however, only a qualitative attribution or estimation has been made according to this method.[27]

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[25] Cf. Kopfmüller, J., Brandl, V., Jörissen, J., Paetau, M., Banse, G., Coenen, R. and Grunwald, A. (2001).

[26] Cf. BIONA (2012).

[27] Cf. Antony, F., Mai, F., Speck, T. and Speck, O. (2012), pp. 175 - 182.

Table 1: Indicator set for the sustainability assessment of biomimetic technical solutions as part of the accompanying project on the BMBF-funded BIONA project[28]

1. Securing human existence				
1.1 Protection of human health	1.2 Ensuring basic services (food, education...)	1.3 Independent livelihood	1.4 Fair distribution of environmental benefits	1.5 Compensation of extreme income and wealth differences
2. Preservation of the social productive potential				
2.1 Sustainable use of renewable resources	2.2 Sustainable use of non-renewable resources	2.3 Sustainable use of the environment as a natural sink	2.4 Avoidance of unreasonable technical risks	2.5 Sustainable development of physical, human and knowledge capital
3. Preservation of the opportunities for development and action of society				
3.1 Equal opportunities with regard to education, occupation information	3.2 Participation in social decision-making processes	3.3 Conservation of cultural heritage and cultural diversity	3.4 Preservation of the cultural function of nature	3.5 Conservation of social resources

The indicators of the 2nd Sustainability Goal "Preservation of the social productive potential" with the numbers 2.1, 2.2 and 2.3 can correspond to resource efficiency goals in their operationalisation, but do not completely cover them (Chapter 2.2).

Additional scientific research on quantifying sustainability was first carried out in 2014 for a biomimetic lightweight ceiling construction from the 1960s.[29] Here, the scientists used the PROSA (product sustainability assessment) method, which takes into account ecological as well as socioeconomic indicators on the basis of a life-cycle assessment. In addition, a life-cycle costing was carried out. The biomimetic ceiling construction was compared with two non-biomimetic constructions, which were state-of-the-art in 2010. Although the results of these studies were presented quantitatively, they were not integrated quantitatively but only discussed qualitatively.

In this first step towards a comprehensive sustainability assessment of biomimetic products, it became clear that the PROSA method is suitable for assessing the contribution to sustainability. Selected environmental impact categories showed advantages of the biomimetic design solution over the alternatives. However, the biomimetic solution performed significantly worse

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[28] Cf. Antony, F., Mai, F., Speck, T. and Speck, O. (2012), pp. 175 - 182.

[29] Cf. Antony, F.; Grießhammer, R.; Speck, T. and Speck, O. (2014).

than the two alternatives in the "land use" impact category. In terms of life-cycle costing, it is rated worse than the more modern ceiling design solutions due to the high labour costs. However, with both methodological approaches, biomimetic solutions can only be evaluated after the development or the application.

In order to raise awareness among young scientists about sustainable technical solutions, the contents of the BIONA projects have been integrated into teaching at the participating universities. In addition, the projects also highlighted the non-material contribution of biomimetics to sustainability: Through biomimetic projects, the cultural function of **biodiversity** and nature – in the sense of a teaching nature – and the respectful handling of it are strengthened.[30] Biodiversity, in turn, is the basis of functioning ecosystems and is indispensable for their resilience. The loss of biodiversity can weaken an ecosystem, which means that ecosystem services can no longer be sustained. However, these are indispensable for the existence of humans, e.g. through nature's capacity to absorb emissions, immissions and waste or by maintaining global material cycles such as carbon, nitrogen and phosphorus.

For this reason, **ecosystem services of nature are defined as part of the natural resources** that can be used and consumed.[31]

2.2 What is resource efficiency?

The term resource efficiency is not always used or understood uniformly nationally and internationally. For this reason, definitions agreed by an expert group of stakeholders and a detailed description of the principles and steps for evaluating the resource efficiency of organisations, products, processes and services have been developed. These can be found in the VDI Resource Efficiency Guidelines (Table 2 on page 24).

Resource efficiency is defined there as the ratio of the benefit of a product or process to its use of natural resources:

[30] Cf. Bertling, J. (2014), p. 169.
[31] Cf. VDI 4800 Part 1: 2016-02, p. 17.

$$Resource\ efficiency = \frac{Benefit_{(product,\ function,\ functional\ unit)}}{Cost_{(use\ of\ natural\ resources)}}$$

Natural resources include renewable and non-renewable primary raw materials, physical space or area, flowing resources such as geothermal energy, wind, tidal and solar energy, the environmental media water, soil, and air as well as ecosystem services.

A **quantitative assessment of resource efficiency** can only be made if the use of natural resources is quantified and correlated with the benefit generated.[32] It is also necessary to quantify the benefits of a product or process.

The **quantification of the use** of natural resources **throughout the entire life-cycle** of a product is a methodological challenge. However, acquisition and measurement via metric systems is well-known and plausible. It can be represented, for example, by the fresh water expenditure [m^3], energy consumption [kWh] or area expenditure [m^2].

The situation is different in the **quantification of benefits**. The benefits of products, processes and services are achieved by features that can often be described by technical variables (see examples). In business, benefits are also often expressed in terms of sales or product prices. Various examples show that other aspects of benefits, such as strategic, social, psychological, aesthetic or cultural aspects, play a major role in purchasing decisions. This is especially the case for electronic products, clothing, furniture or cars. These benefits are difficult to quantify. Therefore, experts have agreed that a **technical assessment of benefits** is preferable to other assessments due to its traceability and that further benefits remain unevaluated.[33]

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32 Cf. VDI 4800 Part 1: 2016-02, p. 30.
33 Cf. VDI 4801: 2016-02 (draft), p. 4.

Examples of technical reference values for a benefit assessment:[34]

Process: For the painting process of metal parts, e.g. the corrosion protection of a sheet steel surface of one square meter under given conditions for ten years could be used as a reference.

Product: For a beverage packaging, the filling volume of 1,000 litres of a carbonated soft drink could be used as the reference value for a defined area of application, e.g. storage or convenience sector.

Service: For a forwarder, the transport of a certain amount of a weight- or volume-related cargo over a certain distance under defined quality criteria such as duration, punctuality, etc., could be selected.

An increase in resource efficiency can usually be achieved

(1) if either **the same benefit** that the functions of a product perform is achieved with less use of natural resources – examples include biomimetic lightweight construction –

(2) or if the **benefit of a product increases with the same amount of resources used** , e.g. via additional technical functions that a product can take over or through solutions with functional integration or synergistic product characteristics. An example of this is lights made of biomimetic sheets, which are vault structured.[35, 36]

Most resource efficiency measures aim to save resources and thus reduce the use of natural resources such as energy, raw materials or water for the same benefit.

Since resources are used throughout the life cycle of a product and, if necessary, consumed, potential savings can be made in every phase of the life cycle (Figure 1). The aim is to optimise the product benefits, not just at specific points in the utilisation phase, but **throughout the entire life cycle** from product manufacture to recycling. Measures to optimise resource efficiency in the utilisation phase of products are often more widespread and better known as solutions for saving resources in the life cycle phases of

34 Based on VDI 4801: 2016-02 (draft), p. 26.
35 Cf. Siteco (2016).
36 Cf. VDI Zentrum Ressourceneffizienz (2016).

product manufacturing or recovering. Reasons this are, for example, statutory efficiency regulations, such as those in the Ecodesign Directive, which focus on the utilisation phase, or better application and marketing opportunities, since the consumer is directly addressed as a user. This also applies in principle to biomimetic solutions. The challenge is to consider the other life-cycle phases more intensively and at the same time. This way is the only way to prevent resource savings in the utilisation phase from being negatively offset by increased resource costs in the product manufacturing and/or utilisation phase.

Example: Through the use of lightweight construction elements when designing a vehicle, fuel can be saved as an energy resource in the utilisation phase of a motor vehicle. However, if the lightweight components are designed as a composite material, the recovery phase is usually resource-consuming. The composite materials used can only be separately recycled at a high recycling cost, i.e. with high material and energy costs.

A **resource efficiency strategy**, which has a significant impact on system-wide resource efficiency, is the strategy of **material substitution**. “Efficiency through material substitution includes the use of secondary raw materials, raw materials with more environmentally friendly and efficient manufacturing processes or from renewable raw materials.”[37] In the latter case, in particular, it has to be checked if and which area competitions occur.

[37] VDI 4800 Part 1: 2016-02, p. 40.

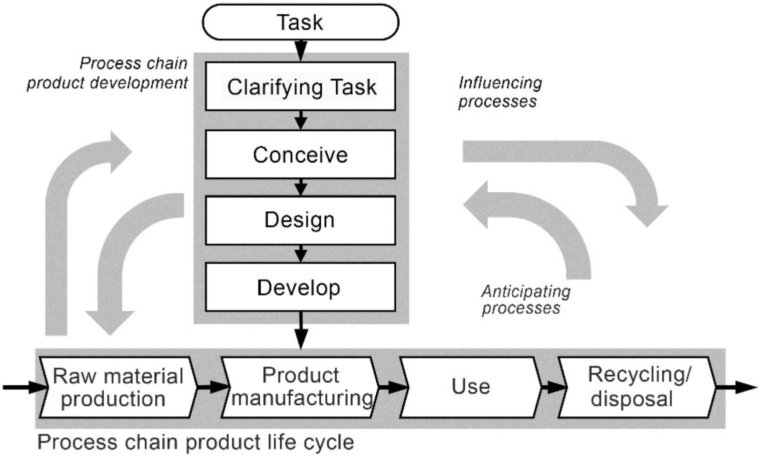

Figure 1: Product development process and product life cycle[38]

Of course, the influence of manufacturing companies is greatest within their own operations in product development, production, and other business areas, followed by direct interaction with customers and suppliers. Product development plays a prominent role in this (Chapter 2.4). This is where product design decisions are made, which in turn determines the resource efficiency of all product lifecycles – from manufacturing and utilisation to recovery and disposal. Thus, designing products of the greatest possible energy- and material-efficiency, durability, reparability, fault-tolerance and recyclability can improve resource efficiency across all life-cycle phases.[39] Through the efficient use of materials and energy, and the optimal adaptation to the respective living environment, biological models and biomimetic solutions derived from them can offer an interesting alternative (Chapter 3.3).

However, the further away other processes and procedures are from the company's own production processes in terms of time and location – such as processes for raw material extraction or disposal – the less influence manufacturing companies have in implementing resource efficiency measures.

[38] VDI 4800 Part 1 : 2016-02, p. 33. Reproduced with permission of the VDI.
[39] Cf. VDI 4801: 2016-02 (draft), p. 8.

Yet, there are many approaches that have been tried and tested to optimise resource efficiency within entire value chains, such as sustainable supply chain management or vertical integration.[40]

Resource efficiency is assessed through raw material indicators[41], energy indicators[42] and indicators for ecosystem services, which together form a basis for assessing the use of natural resources. The VDI guidelines on resource efficiency provide the methodological framework for a resource efficiency assessment (

Table 2). Examples of strategies and resource efficiency measures in production and in the production process supplement the methodological work.

Table 2: VDI Resource Efficiency Guidelines

VDI guideline	Title	Issue date
4800 Part 1	Resource efficiency – Methodological basis, principles and strategies	2016-02
4800 Part 2 (draft)	Resource efficiency – Evaluation of raw material outlay	2016-03
4800 Part 3 (draft)	Resource efficiency – Indicators for the evaluation of environmental impacts	In development
4801 (draft)	Resource efficiency in small and medium-sized enterprises (SME) – Strategies and procedures for the efficient use of natural resources	2016-02
4600	Cumulative energy demand (CED) – terms, methods of calculation	2012-01

2.3 Linking resource efficiency and biomimetics

In order to evaluate the resource efficiency of biomimetic methods or biomimetic products, these solutions have to be compared with other alternatives. Again, the technical benefits, i.e., the function of the solution, must be compared with the expenditure of natural resources.

In production, a company can influence resource efficiency through biomimetic methods or the use of biomimetic products. An example of the use of a **biomimetic product** are self-sharpening blades as tools in a production process (Section 3.3). The self-sharpening effect of the blades creates low cutting forces. The wear and tear of these cutting edges are lower than that

[40] Cf. VDI 4800 Part 1: 2016-02, pp. 22 and 25.

[41] Cf. VDI 4800 Part 2: 2016-03 (draft).

[42] Cf. VDI 4600: 2012-01.

of conventional cutting edges, so the service life of the cutting edges increases and fewer cutting parts are required. These therefore do not need to be manufactured, which goes hand in hand with a saving of material and energy in the utilisation phase of the blades. Whether an increase in resource efficiency can also be observed in the manufacturing and recovery phase of self-sharpening blades compared to conventional cutting parts would have to be determined on a case-by-case basis, depending on the area of application and the material used for the workpiece to be machined.

The application possibilities of **biomimetic methods**, such as the optimisation process for lightweight constructions, **Evolutionary Light Structure Engineering (ELiSE)**, are described in detail in Chapter 3.1. Resource efficiency potentials are raised by lightweight construction solutions by saving material in the manufacturing process of lightweight components. In the case of moving components, this usually results in a reduction in the energy requirement in the utilisation phase. Whether these components are also advantageous in the recovery and disposal process depends on the materials used and the manufacturing process of the lightweight solutions.

The priority goal of companies that have developed new or optimised products using biomimetics is only an increase in resource efficiency per se in a few cases. Nevertheless, if, for example, material and fuel can be saved in the automotive and aircraft industries and the benefits for companies can be directly measured, there is also an influence on the conservation of resources. As a rule, however, biomimetic solutions have not yet been considered in a targeted and quantifiable manner in terms of resource efficiency. But this is possible in principle. Calculations for the quantification of different resource efficiency indicators are not available for the majority of biomimetic solutions or have not been published.

The aim of this brief analysis is therefore to present selected solutions and examples from biomimetics, to systematise them and to consider them consistently from the perspective of resource efficiency. To this end, the resource efficiency potential will be[43] **qualitatively** reported, taking into ac-

[43] Cf. VDI 4800 Part 1: 2016-02.

count the methods and principles according to the VDI guidelines for resource efficiency. The linking of resource efficiency goals and biomimetics is recommended for future innovations, e.g. within the context of a product development process.

One approach can be seen in a European research project on biomimetics and resource efficiency, which was launched in September 2016: The aim of the project is to increase the material and energy efficiency of aircrafts. In addition to the development of a toolset for the design of biomimetic aircraft structures, assembly-oriented production and optimised concepts for repairs, spare parts production, recycling and disposal are essential building blocks of resource efficiency measures. It should be emphasised that measures in this project are to be implemented in all life-cycle phases of an aircraft: In product development, product manufacture, utilisation and in recovery/disposal.[44]A monitoring of the quantification of resource efficiency would be interesting here.

2.4 Biomimetics as a tool in product development

The product development process defines the function, mode of action, design and material of a product. Here, decisions are made about technical, economic and ecological features, such as on manufacturing processes, manufacturing costs, resource consumption, utilisation and recovery characteristics.[45]

When developing and designing technical products, a multitude of different problems have to be solved. The product development process, which is shown in a simplified form in Figure 1, can be further systematised and subdivided into seven steps across all industries (Figure 2):[46]

[44] Cf. K-Magazin (2017).

[45] Cf. Lange, U. and Oberender, C. (2017).

[46] Cf. VDI 2221: 1993-05.

(1) Clarifying and specifying the task, (2) determining functions and their structures, (3) searching for solution principles and their structures, (4) dividing into feasible modules, (5) designing the key modules, (6) designing the entire product, (7) prepare production and operating instructions.

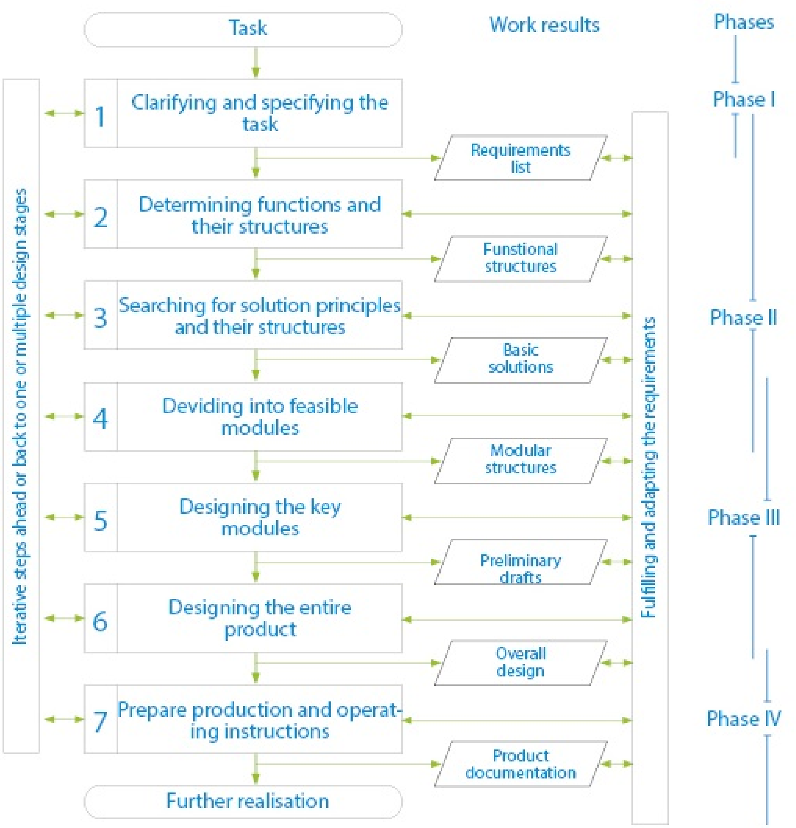

Figure 2: General procedure of methodical development and construction[47]

Various internal and external company objectives are closely related, particularly in the problem-solving steps (1) to (3): More or less well-known pa-

[47] Cf. VDI 2221: 1993-05, p. 9. Reproduced with permission of the VDI.

rameters are collected, compared and specified. Subsequently, different creativity methods, including a well-known technology portfolio, are used to propose solutions. These often depend significantly on the level of knowledge and information of the working team.

Process of biomimetic working – biomimetic development process

Biomimetics can significantly expand the solution scope and provide new, creative approaches to both the product to be developed and alternative production processes. For example, biomimetics can be regarded as the building block of an innovation process. In particular, it should enable the transition from basic biological research to applied technical research and development in order to produce technical solutions.[48] However, this requires a high degree of interdisciplinary and cooperation. Due to different scientific, methodological and conceptual starting positions of, e.g., engineers, biologists, physicists, biochemists, physicians, and computer scientists, a biomimetic development process may need more time than a conventional approach.[49] Big companies, in particular, who are open to biomimetics are willing to accept this additional effort because they have high expectations of the innovation potential of biomimetic solutions. By contrast, small and medium-sized enterprises (SMEs) often do not have the appropriately qualified product developers and the financial means to independently carry out projects on biomimetic alternatives and to integrate biomimetic solutions into their product development. Development engineers often lack the necessary biological foundations. However, outsourcing the search for biological solutions to external scientists is generally not expedient since, in turn, they do not have the company-specific product and process knowledge.[50] For this reason, close cooperation between biomimetics experts and company employees is required (Chapter 4).

The process of biomimetic work is shown in Figure 3. The straight-line and incremental process flow shows an idealised case; often the process of biomimetic work is iterative and characterised by repetitive processing loops.[51]

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[48] Cf. Bertling, J. (2014), pp. 150 - 153.
[49] Cf. Bertling, J. (2014), p. 157.
[50] Cf. Banthin, H. (2014), pp. 40 - 41.
[51] Cf. VDI 6220 Part 1: 2012-12, p. 24.

The first step in solving a technical problem with the help of biomimetics is an intensive, interdisciplinary discussion. Together, ideas are developed with the aim of bringing together a technical solution and a biological model. Starting points can be insights from basic biological research. Then, like the Lotus Effect®, it's a biology push. If the impulse for a biological solution is given by a technical problem, then this is a technology pull approach. The aim of this approach is often the improvement or further development of a product or production process.[52] The result of the biomimetic work can be considered as a possible solution in the product development process and thus expand the solution scope (Figure 2, Level 4).

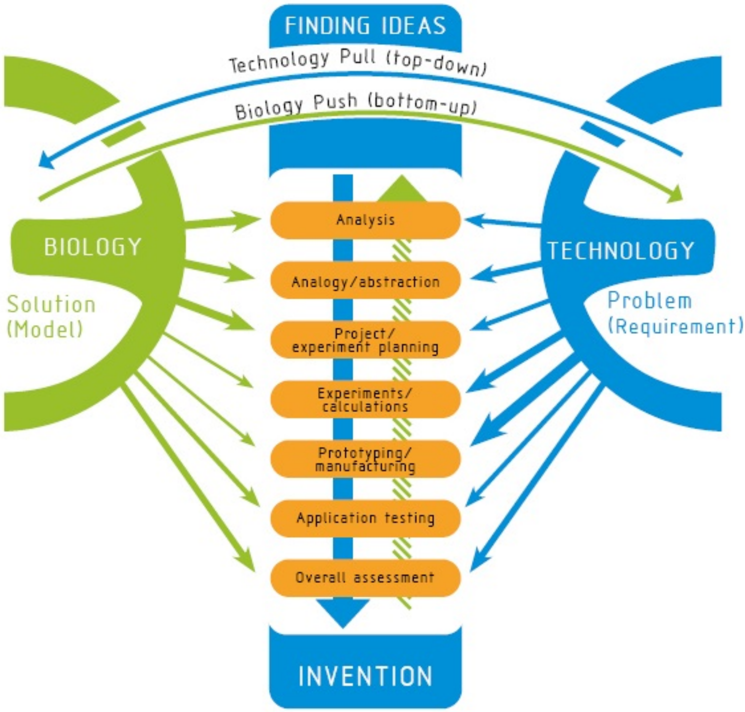

Figure 3: Simplified process of a biomimetic development up to invention[53]

[52] Cf. VDI 6220 Part 1: 2012-12.

[53] Cf. VDI 6220 Part 1: 2012-12, p. 24. Reproduced with permission of the VDI.

The brainstorming phase is followed by the analysis phase. From the multitude of organisms, structures and functions – supported by engineering and scientific methods, procedures and possibly experiments – potential biological solutions are identified, which are examined for their transferability to the technical problem and evaluated. The subsequent phase of abstraction or analogy creation forms the core of biomimetic work: In analogy creation, all aspects of physical quantities, as well as “soft” factors of the biological and technical systems, are compared and contrasted. Subsequently, the relationships and interactions of these aspects within the respective systems in the sense of building up a relationship network are examined. This often requires abstractions so that the relevant functional aspects can be identified. Finally, the biological and technical relationship networks are superimposed to compare both systems. Appropriate analogies are found this way and possible solutions are determined. Biomimetic solutions would often not have been found by a classical design approach. The further process of biomimetic work does not differ significantly from the classical development process in production.

A special feature compared to many classic product development processes concerns the necessity of an interdisciplinary development team or interdisciplinary trained employees.[54] This still presents companies with major challenges, since training is generally not designed for interdisciplinarity.

[54] **Cf. VDI 6220 Part 1: 2012-12.**

3 TECHNICAL APPLICATION OF BIOMIMETICS

As described above, the approaches and uses of biomimetics are very diverse and complex. Therefore, in the following, an overview of the use of **biomimetic methods** will be given, which can be used to design and optimise products. In addition to the biomimetic methods (Chapter 3.1) there are a variety of biomimetic products (Chapter 3.3), which were produced with the help of biological models.

3.1 Biomimetic methods

Biomimetic methods or processes are used primarily in the optimisation of components, but also in the development of new designs. These methods differ from individual biomimetic products, which can be deduced more or less directly from functional principles of biological models. Biomimetic methods can be applied regularly in the production process with a specific goal **without the need for an additional biomimetic development** (Figure 3).

Evolutionary algorithms

The model for evolutionary algorithms (EA) is biological evolution with the mechanisms of mutation, selection and recombination. Although evolution is a fundamentally undirected process that does not aim for the optimum, the result of evolution are organisms that can adapt to changing environmental conditions over many generations. If environmental conditions remain unchanged, species only change slightly in terms of genotype (as determined by the DNA) and phenotype (regarding the appearance of an individual). The mechanisms of evolution, such as mutation, selection, recombination, and variation, are translated into mathematical, computer-aided models and algorithms.[55]

EA take into account a specific optimisation target specified in the algorithm and approach it over several generations. For this purpose, the principles of variation (mutation and recombination) and selection are expressed mathematically and performed iteratively in a computer-aided loop. Variation provides diversity and selection sets the direction for evolution. The variants of

[55] Cf. VDI 6224 Part 1: 2012-06.

the offspring that have best approached the optimisation goal are the new parents.

Biomimetic method: Evolutionary algorithms

Goal	System improvement and optimisation
Biological model	Processes of evolution
Functional principle	Mutation, selection and recombination are prerequisites for the adaptation of the offspring to changed environmental conditions
Biomimetic method	Algorithms that map the evolutionary processes; iteratively generated "parents" generate descendants with new properties, which are selected according to the optimisation target
Resource efficiency potential	Resource efficiency can be an optimisation goal
Additional benefits	Solutions of multi-dimensional or multi-criteria optimisation problems (criteria such as costs, time, resource efficiency), for which there are no standard procedures
Stage of development	Market maturity, standardisation

EA can often be used in product development as an additional tool to find an optimal solution. In principle, all conceivable technical and non-technical issues can be dealt with. This also applies to the optimisation of multiple goals (multi-criteria), which may conflict with each other and are not comparable. Examples include the price, the CO_2 emissions and the engine power of a used car. Criteria for resource efficiency such as material or energy savings can also be incorporated into the algorithm as optimisation goals.

EA are usually used when

- there are no known standard solutions for the optimisation problem or there are no conventional algorithms for it,
- the known standard solutions cannot be used successfully or
- the solution of the optimisation problem with conventional methods is too expensive.[56]

Multi-dimensional optimisation problems can be solved with EA. They are particularly suitable for problems that are extremely complex and not analytically solvable or can only be explained experimentally. There are no

[56] Cf. VDI 6224 Part 1: 2012-06.

standard methods for such problems because, for example, there is no objective function that can be formulated mathematically or there is no gradient information.[57] A well-known example illustrating the EA process is the optimal optical converging lens, which is not an ideal thin lens. Light rays are refracted differently in a glass body. If the thicknesses are set correctly in the corresponding places by the method of the EA, the rays are broken, so they all come together in one point. Further examples of various optimisation problems can be found in the guideline VDI 6224 Part 1.[58]

Contribution to resource efficiency: The application of EA can always contribute to resource efficiency if the conservation of a resource is taken into account as an optimisation target in the execution of the algorithm. This is also possible with conflicting goals. In these cases, EA will find the best possible or most efficient solution, taking into account the particular objectives set.

Biomimetic structure optimisation with algorithms

Biological load bearers such as trees and bones are optimally adapted to their respective load. The same design principles as the axiom of constant stresses apply to all of them.[59] The biological models are able to store material "on the job" at the sites where high loads occur (trees) and to degrade it in less load-bearing areas (bone). Due to the constantly distributed stresses, endurance failures caused by recurring loads can be avoided.

Biomimetic structure optimisation uses these natural principles to transfer them to load-bearing components. Component properties that are to be optimised in this case are mass, strength, rigidity or service life. From the growth principles of biological models, scientists at the Karlsruhe Institute of Technology (KIT) have derived three biomimetic methods and transferred them to computer simulations based on the finite element method (FEM). These

[57] Cf. Seitz, H. (2013), p. 37.
[58] Cf. VDI 6224 Part 1: 2012-06.
[59] Cf. VDI 6224 Part 2: 2012-08.

methods can be used to achieve topography, topology and fibre composite optimisation:[60, 61]

(1) **CAO: Computer-aided optimisation (design optimisation)**
Reduction of component-damaging stresses during construction. Locally occurring stress peaks are broken down by depositing material in notch areas until a uniform surface tension is achieved.

(2) **SKO: Soft Kill Option (weight optimisation)**
Topology optimisation based on the model of bone growth, in which the inner part of a component is changed. Areas of high stress are reinforced and stiffened; low-stress areas are removed.

(3) **CAIO: Computer-aided internal optimisation (material optimisation)**
Fibres of technical components must be oriented along the force flow so that the potential of fibre composites can be optimally exploited. The fibre flow must not be severed by geometric disturbances such as holes. This is achieved by the deflection of fibres at the disturbances, so the fibres are only loaded in terms of tension and compression, and the unfavourable shear between them is minimised. In this way, the required strength can be achieved with as little material as possible.

A detailed description of the procedures with references to the implementation in the FEM and application examples are given by the norms and standards of the VDI and DIN/ISO.[62, 63]

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[60] Cf. Mattheck, C. (2006), p. 51 et seqq.
[61] Cf. Mattheck, C. (2010), pp. 23 - 31 and pp. 104 - 110.
[62] Cf. VDI 6224 Part 2: 2012-08, p. 8 et seqq.
[63] Cf. DIN ISO 18459: 2016-08, p. 12 et seqq.

Biomimetic method: Biomimetic structure optimisation with algorithms

Goal	Optimal design of components, including mass, strength, rigidity, and service life
Biological model	Growth and degradation of material in trees and bones
Functional principle	Material accumulation and material degradation depending on the load
Biomimetic method	Algorithms for notch and shear stress reduction, stress homogenisation, fatigue strength and material savings in unloaded areas
Resource efficiency potential	Material savings in product manufacturing, energy savings in the utilisation phase
Additional benefits	Longer product service life thanks to higher stability, weight savings of the products
Stage of development	Common optimisation method, especially in the automotive industry

Biomimetic structural engineering optimisation has become a standard procedure for lightweight applications in the mobility industry. However, these optimisation methods do not provide information about material strength or quantitative load values. Direct proof of the strength of the component still has to be made through technical calculations or mechanical experiments.[64]

An overview of applications and their relation to resource efficiency can be found in the VDI ZRE brief analysis No. 17 “Resource efficiency in lightweight construction”.[65]

Contribution to resource efficiency: The aim of the methods for structure-mechanical optimisation is to save material and weight for the same or better service life of the components, thereby reducing production and material costs. In individual cases, significant weight savings of up to 50 percent can be achieved, especially with load-bearing components in the automotive and aircraft industries. As these are moving objects, biomimetic lightweight construction can also reduce fuel consumption during the utilisation phase.

Biomimetic structure optimisation with graphic methods – thinking tools based on nature

Using the computer-based methods (CAO, CAIO and SKO) to optimise components based on the model of nature, simple methods have been developed, which only require a pencil, paper and a protractor. Goals include avoidance of cracking and crack propagation through stress reduction, but also fatigue strength and lightweight construction. The principle of these thinking tools

[64] Cf. Mattheck, C. (2010), p. 177.

[65] Cf. Kaiser, O. S., Krauss, O., Seitz, H. and Kirmes, S. (2016), p. 62 et seqq.

lies in the realisation that the 45-degree angle can be regarded as a secret natural constant. This allows the representation and conversion of shear, tension and compression for simple optimisation problems.[66]

Biomimetic method: Biomimetic structure optimisation with graphical methods (shear squares, tension triangles and force cones)

Goal	Form finding of mechanical lightweight components without a computer
Biological model	Derived from the growth and degradation of material in trees and bones
Functional principle	Material accumulation and material degradation depending on the load
Biomimetic method	Abstraction through geometric representation of the force distribution and derivation of the most favourable design space in terms of lightweight construction
Resource efficiency potential	Material savings in product manufacturing, energy savings in the utilisation phase
Additional benefits	Software-independent method for obtaining design space and design proposals for lightweight solutions
Stage of development	In application

With the so-called **shear squares** thinking tool, force distributions in components or in other mechanically loaded objects can be displayed without the use of computers. This method helps to analyse and understand force distributions. The force distributions of the tensile stress, which act on the components when they are pulled apart, and the compressive stresses that occur when they are compressed can be graphically represented. If these stresses are too high, the component fails.[67] Various applications of the method of shear squares are shown in Figure 4. It can be clearly seen that the tensile and compressive stresses always act on the components at an angle of 45 degrees. This method can be used even for torsional shear stresses.[68]

[66] Cf. Mattheck, C. (2010), p. 213 et seqq.

[67] Cf. Mattheck, C. (2006), p. 4.

[68] Cf. Wissner, C. (2010), p. 26.

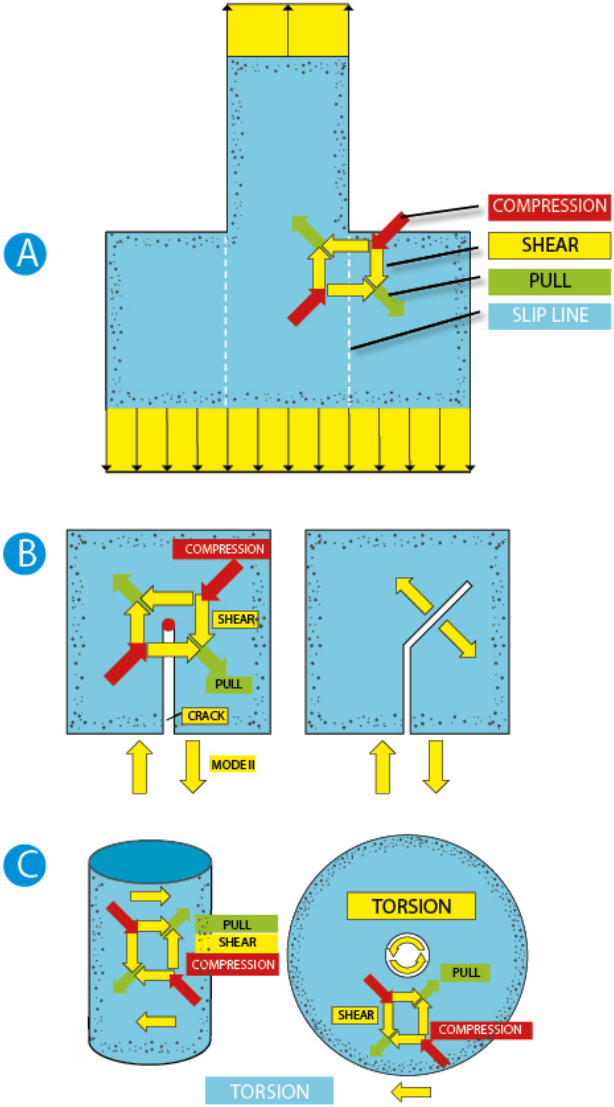

Figure 4: Examples of the use of shear squares in components (A: tensile stress, B: shear crack, C: torsion)[69]

[69] Cf. Mattheck, C. (2006), p. 4.

These 45-degree angles can be observed almost everywhere in nature. There, too, they counteract the shear and ensure the stability of the respective elements in the flora and fauna. Examples of this are the arrangement of the side veins in leaves, the branching of the tree roots or the feather quills arranged on the quill in birds.[70]

The method of **tensile triangles** is used in component development to reduce notch stresses by rounding off. The biological model is provided by the curves in the branch forks of the trees or their rounded anchoring in the soil. Instead of the commonly used rounding in the form of a quadrant, a first triangle with the base angle of 45 degrees is placed over the notch. The next angle set in the direction of pull has a half base-angle of 22.5 degrees, and so on. The resulting shape can be scaled to any space (Figure 5).[71] It could be proven both computationally and experimentally that the stress peaks that exist in quadrant transitions are removed by using the method of tensile triangles. Components such as screws, shaft shoulders or fork levers have a longer service life at points with high stress by this method.[72]

Just as the tensile stress in heavily loaded areas can be relieved by biomimetic notches, non-bearing areas or areas that are free of force distribution can be removed. The process remains the same, but the tensile triangles do not allow the component to grow, but shrink instead.[73]

[70] Cf. Mattheck, C. (2010), p. 46 et seqq.

[71] Cf. Mattheck, C. (2017), p. 90.

[72] Cf. VDI 6224 Part 2: 2012-08, pp. 18 - 22.

[73] Cf. Mattheck, C. (2010), pp. 67 - 69.

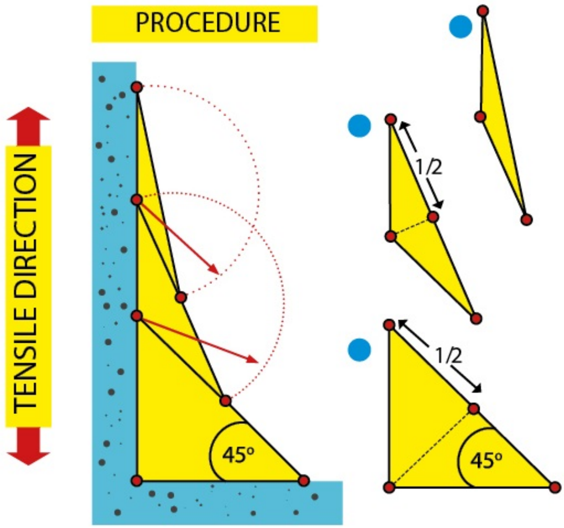

Figure 5: Graphical procedure for the optimisation of notches with the method of tensile triangles[74]

The **force cone method** is another thinking tool for computer-free design. It complements the method of the Soft Kill Option (SKO). When using the force cone method, usually similar design proposals arise as using the computer-aided SKO method. The goal is to find stable lightweight solutions while maintaining a functional understanding of structural elements.[75] The method is based on the assumption that a 90-degree pressure cone is pushed in front of each force, and a tension cone is pulled behind the force. This can be graphically represented by drawing the pressure and tension cones that act on a planned component. Primary points are sketched at the cone edges – where tensile and compressive forces intersect at right angles. At these points, struts and tension cables are drawn, which ultimately lead to a design proposal for the component.[76] This form of design generation helps to illustrate the force distributions without special mechanical knowledge. For example, the stress type of compression struts can be easily recognised and

[74] Cf. Mattheck, C. (2017).

[75] Cf. Haller, S. (2013), p. 37 et seqq.

[76] Cf. Mattheck, C. (2010), p. 131 et seqq.

helps to better investigate structural parts of other methods. However, this method cannot take into account geometric limitations of the installation space.[77]

Contribution to resource efficiency: Nature's thinking tools are simplified biomimetic structure optimisation methods that have similar resource efficiency potentials as the previously described algorithmic methods.

Biomimetic structure optimisation within an integrative product development process using ELiSE

Based on a large number of variations in the shell structures of various marine plankton organisms such as diatoms and radiolarians, the optimisation method for lightweight construction **Evolutionary Light Structure Engineering (ELiSE)** was developed. The shell structures of the biological models are very light and stable. They must protect themselves against predators and water pressure as well as float on the water surface in order to obtain enough light for their metabolism. The structures of the diatoms were evaluated for their lightweight properties and recorded in a database. The scaling of the microscopic lightweight structures to large components is possible because the material cross-section and surface pressure scale with the square of the linear scale. This allows the transfer to almost all technical applications.[78]

This procedure for lightweight applications was already mentioned in various short analyses of the VDI ZRE due to its high resource efficiency potential. [79, 80]

[77] Cf. Haller, S. (2013), p. 123.

[78] Cf. Hamm, C. E., Merkel, R., Springer, O, Jurkojc, P., Maier, C., Prechtel, K. and Smetacek, V. (2003).

[79] Cf. Kaiser, O. S. and Seitz, H. (2014), p. 20.

[80] Cf. Kaiser, O. S., Krauss, O., Seitz, H. and Kirmes, S. (2016), pp. 64 - 65.

Biomimetic method: Biomimetic structure optimisation within an integrative product development process using ELiSE

Goal	Innovative lightweight solutions
Biological model	Shell structures of diatoms (diatoms, radiolarians)
Functional principle	Shell structures made of silicon dioxide
Biomimetic method	Five-stage construction methodology: Screening and abstraction of the diversity of the shell structures are a building block of the ELiSE procedure for structure optimisation[81]
Resource efficiency potential	Material savings in product manufacturing, energy savings in the utilisation phase, and further resource efficiency goals can be taken into account in the optimisation
Additional benefits	Component designs that would not have been created using conventional methods
Stage of development	Method available and is used in enterprise collaboration

The ELiSE process has been developed, standardised and partially patented in recent years as a method for complex biomimetic product development processes in lightweight construction.[82] In the product development process, this process combines various biomimetic and classical methods in order to obtain optimally adapted components (Figure 6). The goal is to consider the entire value chain in this product development process in the future. In this holistic approach, economic efficiency, conservation of resources and recyclability are to be incorporated.[83]

The procedure of the process is analogous to the general procedure of methodical development and construction. It is also found in the process of biomimetic work (Figure 3 on page 29). In the ELiSE procedure, the process was divided into five systematically building steps, the core of which is the screening of biological models from the structural and lightweight database of diatoms:

(1) Analysis of the component to be optimised,

(2) Screening and abstraction of biological models with search for analogies,

(3) Concept development based on the design principles found,

(4) Optimisation with biomimetic and classical optimisation methods and

[81] Cf. Alfred Wegener Institute (2016).
[82] Cf. VDI 6224 Part 3: 2016-04 (draft).
[83] Cf. Kaiser, O.S., Krauss, O., Seitz, H. and Kirmes, S. (2016), p. 65.

(5) Evaluation and prototype or product development.[84]

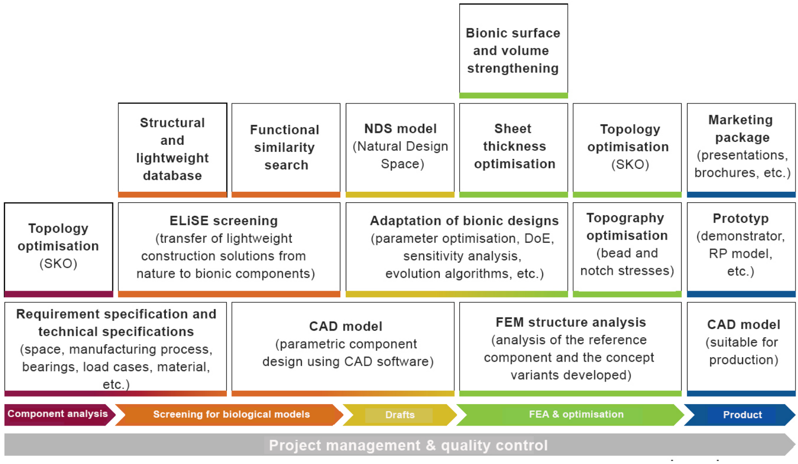

Figure 6: Schematic of an advanced biomimetic product development process based on the ELiSE method[85]

There are several innovative design proposals for components in step three thanks to the ELiSE process, which would not have been created by conventional design methods. These designs will be reviewed with regard to the required specifications and further developed if necessary. The invention process usually ends before the development and market launch of the optimised product.

Contribution to resource efficiency: The special feature of the ELiSE process is that the entire life cycle should be considered and taken into account during product manufacture. Criteria for resource conservation of raw materials, energy and water can be introduced at the beginning of the product development process and taken into account in product manufacture. Since it is basically a method for biomimetic lightweight construction, material and weight will be saved while maintaining or improving the service life of the components, thus reducing the production and material costs. This results in

[84] Cf. VDI 6224 Part 3: 2016-04 (draft), p. 8.

[85] VDI 6224 Part 3: 2016-04 (draft), p. 9. Reproduced with permission of the VDI.

a reduction of the energy demand in the utilisation phase for mobile products. Using the example of optimising the foundation structure of a wind power plant, weight savings of 48 percent were achieved as opposed to a comparable foundation structure.[86]

3.2 A model for many applications

Regardless of whether biomimetic developments result from basic research (biology push) or as an answer to technical questions (technology pull): First, the natural working principle is analysed. The technical abstraction of these biological principles often leads to a fundamentally different understanding of modes of action and mechanisms. This insight can – as the example of the Lotus Effect® shows – lead to a paradigm shift and innovation leaps.[87] Superhydrophobic surfaces are not smooth, but have a rough nanostructure, which greatly reduces a contact surface with the wetting liquid. Liquids run off almost unhindered leaving a dry surface. This discovery led to a paradigm shift. Many self-cleaning and liquid-repellent surfaces were then fitted with a rough structure. This finding also brought with it a leap in innovation, with the result that more than 200 side-innovations have emerged from the Lotus-Effect® to date.[88]

This example illustrates that the analysis of a biological model often not only develops a single special biomimetic product, such as facade paint, touch fasteners, dowels or car tyres, but that a functional principle can lead to a variety of uses in many different industries. Table 3 illustrates a selection of well-known biomimetic functional principles and their implementation.[89] In chapter 3.3, individual application examples are described in more detail and, in particular, with their significance for resource efficiency.

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[86] Cf. Kaiser, O. S. and Seitz, H. (2014), p. 20.
[87] Cf. Barthlott, W. (2017).
[88] Cf. Speck, T. and Erb, R. (2011), p. 111.
[89] Cf. Seitz, H. (2013), pp. 40 - 41.

Table 3: Examples of different products based on the same functional principle

Brand	Functional principle	Product	Applications
Fin Ray Effect®	Tail fins of bony fish bend at lateral pressure against the pressure direction. Flexible, elastic, and connected longitudinal beams move at the same distance against each other. That results in a positive locking to the pressure-exerting object.	Vileda mop PowerPress® Vileda slalom dust wiper	Domestic appliances
		Backrest of the car seat, BMW Group	Automotive Industry
		Festo AG:[90] e.g. gripper DHDG, Airacuda, Air_ray, AquaJelly, AirJelly	Automation technology, robotics
Vault structuring	Structure of honeycombs and other hexagonal structures are very stable and light. Thin sheets or films automatically form six- or octagonal structures at low pressure, which are stable, flexible and elastic: Lightweight construction with low material usage.	Honeycomb drum from Miele	Domestic appliances
		Catalytic converter housing for motorcycles: Emitec "lightweight catalyst"	Vehicle construction
		HEXAL light from SITECO with functional integration	Lighting technology
		3D roof construction of the sports centre in Odessa	Architecture
Lotus Effect®	Superhydrophobic self-cleaning micro- and nanostructured rough surfaces of plants such as lotus or nasturtium. Rough instead of smooth technical surfaces.	Lotusan facade paint and facade coat from Sto AG Erlus Lotus® clay roof tiles from Erlus	Construction industry
		Dirt-repellent textiles from the Hohenstein Institute	Technical textiles, clothing
		Glass coatings for toll system cameras from Ferro GmbH	Traffic-control technology
Gecko Tape®	Toes of geckos are equipped with lamellae and fine hairs in the nanometre range. They produce a reversible adhesion by van der Waals forces. Nanostructured, self-organising technical hairs provide very strong but reversible adhesion to smooth surfaces.	Gecko® tape for reversible adhesion from Binder GmbH	Various industries
		Adhesive pads for climbing on smooth facades; developed by Stanford University	Work on smooth interior and exterior facades, leisure activities if applicable
		Festo NanoForceGripper for the automatic transfer of mobile phones (detachment with the FinRay Effect®)	Automation technology

[90] Cf. Festo (2017a).

3.3 Biomimetic products and solutions

In the following, a selection of biomimetic products and prototypes with a particular focus on resource efficiency is presented. The specific innovation goal is formulated at the beginning. It is the starting point for a solution search in the context of a product development process. The biological functional principle and the technical implementation will be briefly explained. If this can be deduced from the available sources, the resource efficiency potential of the biomimetic solution is qualitatively evaluated, and the life cycle phase with the relevant impacts is named. Additional benefits that go beyond the aspects of resource conservation or resource conservation are also mentioned.

3.3.1 Material utilisation and material substitution

Inherently stable and bending elastic components

A structure that is common in nature and is formed by self-shaping is the regular hexagon. Examples can be found from the structure of the benzene ring to honeycombs to the sea turtle shell. The hexagonal structure of honeycombs spontaneously forms from a round shape at a temperature of about 40° C generated by the bees.[91] Hexagonal structures have many advantages: They are stable with low material usage and use the existing surface optimally. Thin-walled materials such as metals, plastics, cardboard and paper form the so-called hexagonal or octagonal vault structure in a cylinder under pressure by themselves.[92]

Conventional processes such as rolling, embossing or hydroforming have high levels of plasticisation and low reserves for secondary forming or crash. Expensive and complicated tools and machines are usually required for production. In vault structuring, the structure spontaneously forms in the material with minimal plasticisation. The material assumes the most energetically favourable shape. The structured films and sheets have a high flexural rigid-

[91] Cf. Pirk, C. W. W., Hepburn, H. R., Radloff, S. E. and Tautz, J. (2004), pp. 350 - 353.

[92] Cf. Dr. Mirtsch GmbH (2009).

ity with smaller wall thickness. The noise of walls and components is minimised, and heat and mass transfer is improved. In addition, vault-structured components have a high surface quality and glare-free light reflection.[93]

Biomimetic product: Vault structured sheets and films

Goal	Inherently stable and bending elastic components sheets and foils for a variety of applications
Biological model	Self-structuring honeycombs made of wax, profiled back shell of turtles
Functional principle	Self-structuring under certain environmental conditions
Technical implementation	Self-forming of sheets or plastic films to hexagonal or octagonal structures under negative pressure (biomimetic vault structuring)
Resource efficiency potential	Material savings in product manufacturing, energy savings in the utilisation phase (depending on the end product)
Additional benefits	Preservation of the surface quality during deformation, higher natural frequency range
Stage of development	Various products on the market

Dr. Mirtsch GmbH offers the vault structuring process as a service in product development for companies. These cooperations have already resulted in a large number of innovative and efficient products. Selected examples are listed in Table 3.

Contribution to resource efficiency: Depending on the product, significant material savings of 30 percent or more in the production phase are possible thanks to the more flexible, elastic and inherently stable lightweight construction. In the production process of the structured sheets or foils, only one tool is needed to produce structured continuous sheets or foils under vacuum. Compared to embossing or stamping processes, the vaulting process saves tools and process steps and thus material and energy. In the utilisation phase – due to the lightweight components in moving end products – an energy saving can be achieved.[94] Products made from aluminium sheets rather than other metals or composites could be better recycled if necessary. This would have a beneficial effect on resource efficiency in the recovery phase. On the other hand, resource expenditures for alternative materials are still incurred in the product manufacturing phase. These would have to be considered in a comprehensive resource efficiency analysis.

[93] Cf. VDI Zentrum Ressourceneffizienz (2016).
[94] Cf. Dr. Mirtsch GmbH (2017).

Lightweight components for aircraft construction

Slime moulds grow from a central point in the direction of accessible nutrients and thus spread like a net. In this two-dimensional network, various nodes form, which are connected with a minimal number of mucous threads. From this biological growth process, developers at Airbus have developed an algorithm that helps to optimise a cabin partition that separates the attendant from the passengers during the flight. With the help of the algorithm, the connection points of the partition constructed of individual struts can be optimally linked. In addition, the junctions and forms of the struts are optimised based on the model of bone growth. The resulting bio-computation process provides a variety of design proposals that can be evaluated and developed further.[95]

Biomimetic product: Cabin partition for Airbus A320

Goal	Weight reduction of components in aircraft construction
Biological model	Slime fungus growth, bone growth
Functional principle	Hierarchically organised structural connections of natural growth enable stable lightweight construction
Technical implementation	Algorithm derived from various natural growth principles; 3D printing from Scalmalloy®
Resource efficiency potential	Material savings in production, energy savings in the utilisation phase, recyclable at the end of product life
Additional benefits	Weight reduction
Stage of development	Prototype, test series completed, first test flight planned

For technical implementation, together with its subsidiary APWORKS, Airbus has developed a high-performance aluminium powder, the so-called Scalmalloy, which can be used in 3D printing (additive layer manufacturing, ALM). The components made from it are almost as strong as titanium.[96] To complete the project, 116 individual components are additively manufactured and bolted. This is necessary because a cabin partition cannot be printed in one piece, not least because of the size.

Federal Minister for Environment Hendricks honoured the biomimetic cabin partition on 28 November 2016 with the Federal Ecodesign Award in the

[95] Cf. Ars Electronica (2016).
[96] Cf. APWORKS (2017).

"Concept" category. The reasons were the outstanding lightweight construction and the associated fuel savings during the utilisation phase.[97]

Contribution to resource efficiency: Through additive manufacturing, significant material savings could be achieved in the production phase, which led to a weight reduction of 45 percent (30 kg) with the same strength in comparison to previous conventionally manufactured partitions. Airbus estimates that the lighter-weight component can save approximately ten tonnes of CO_2 emissions per aircraft per year during its utilisation phase.[98] In addition, Scalmalloy is fully recyclable.

Facade shading

Movable structures are the basis for most complex technical products. Relatively simple movements such as opening and closing are usually implemented with joints of hinges, rigid bars and plates as well as an (electric) motor. These moving structures often have to be made mobile with lubricants and wear out in the utilisation phase.

Opening and closing are mechanisms that are very common in nature. For example, carnivorous plants close very quickly once a prey has landed on them. Petals, spruce cones and seed vessels have different opening mechanisms, which do without additional components and work due to flexible, elastic structures. The bird-of-paradise flower (Strelitzia) has become the focus of research. This flower comes from South Africa and is pollinated by birds. To do this, they settle on a perch formed by the flower, which is formed from petals that have coalesced together. Due to the weight of the bird and the pressure down, the petals open and the plant releases pollen that sticks to the plumage of the bird. So the bird can transfer the pollen to the next flower.[99] This effect is particularly interesting as tests have shown that the flower of the Strelitzia can be bent up to 3,000 times without material failure.[100]

97 Cf. HamburgAviation (2016).
98 Cf. Airbus (2017).
99 Cf. Baulinks (2014).
100 Cf. Speck, T., Speck, O., Neinhuis, C. and Bargel, H. (2012), pp. 104 - 105.

Biomimetic product: Flectofin®

Goal	Maintenance and wear-resistant shading system for large and complex buildings
Biological model	Elastic deformation mechanism of the bird-of-paradise flower
Functional principle	Petals connected in the middle fold over elastically during pollination (pollination by birds, their weight bends the perch)
Technical implementation	Slats of fibre composite attached to a deformable centre bar; elastic deformation of the rod produces continuous opening and closing of the slats
Resource efficiency potential	Material savings in product manufacturing, material and energy savings in the utilisation phase
Additional benefits	Time savings through long maintenance intervals, continuous control
Stage of development	Model “One Ocean”; so far no other products known

This folding mechanism, its abstraction and technical implementation served as the biological model for the development of the facade shading Flectofin®. For this purpose, highly elastic slats made of fibreglass composite material were developed, which can be moved without joints or hinges. For the slats, several layers of material were laminated one above the other. At one edge, there is a stiff spine and opposite an elastically deformable sheet. When a force is applied to the spine, the tension in the material folds the sheet over. Depending on the extent of the deformation, the sheet will shade the facade completely or only partially.[101] This shading system was shown in 2012 at the “One Ocean” theme pavilion at the World Expo in South Korea.[102]

This folding mechanism is an important development in the construction industry, but it represents a material failure in the actual understanding of engineering science. The classic approach is to prevent a component from bending significantly under heavy load. Without biological inspiration, this form of facade shading would probably never have occurred. Flectofin® is suitable for use in large, tall utility buildings such as office buildings and production halls.

Contribution to resource efficiency: Raw materials are saved in the manufacturing phase, since the biomimetic facade shading consists of fewer components than classic shading systems. In the utilisation phase, Flectofin® is basically maintenance-free, in contrast to classic shading systems, and shows virtually no wear. Lubricants can be completely dispensed with. The

[101] Cf. Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T. and Knippers, J. (2011).

[102] Cf. University of Stuttgart (2012).

deformation requires relatively little energy and can be controlled by sensors depending on the amount of sunshine. Thus, energy and material are saved in the utilisation phase of the shading system.

Self-sharpening blades

Rodent teeth have become efficient chewing and cutting tools over the course of millions of years. Despite their relatively low intrinsic hardness, these teeth are able to cut hard materials. This is attributed to a tooth structure with combined materials: An enamel layer on the anterior surface of the tooth (hardness: HV 400) and an about half as soft tooth core made of dentin (hardness: HV 200) are perfectly interlocked by a spatial grid and graded in their hardness. As a result, the teeth achieve a great effect. The thin enamel layer forms the free surface during cutting, and it is supported and stabilised by the exposed dentin.[103] This tooth structure is also responsible for the self-sharpening effect of the teeth. Due to the directed wear of the dentin, which is softer than enamel, a hard enamel layer remains at the tooth leading edge and produces a sharp cutting edge.[104, 105]

Biomimetic product: Rodentics®

Goal	Self-sharpening blades for industrial use
Biological model	Teeth of rodents with soft inner dentin and hard external enamel
Functional principle	Self-sharpening by directed abrasion
Technical implementation	Blades made of two material components: inside: carbide, outer layer: ceramics
Resource efficiency potential	Material and energy savings in the utilisation phase
Additional benefits	Longer maintenance intervals, thereby saving time
Stage of development	In use

The natural regrowth of the teeth compensates for a high tooth wear. This biological principle was used in the development and design of tools for cutting applications by Fraunhofer Institute for Ceramic Technologies and Systems (IKTS), Fraunhofer Institute for Surface Engineering and Thin Films (IST), Fraunhofer Institute Production Technology (IPT) and Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT). Here, different material combinations of the self-sharpening blades were tested for

[103] Cf. VDI 6220 Part 1: 2012-12, p. 14.
[104] Cf. Gäbler, J., Kusumah, I. and Pleger, S. (2007).
[105] Cf. Fraunhofer UMSICHT (2017).

specific workpiece applications. Meanwhile, the blades are in mass-production and are in practical use.[106, 107]

Contribution to resource efficiency: The self-sharpening effect of the blades created low cutting forces. The wear amounts of the self-sharpening edges are lower than with conventional blades, so the service life of the cutting edges is increased and fewer cutting parts are required. These therefore do not need to be manufactured, which is associated with material and energy savings. The resource efficiency potential in the production phase of self-sharpening blades, compared to conventional cutting parts, would have to be determined on a case-by-case basis, depending on the area of application and the material used for the workpiece to be machined.

Optimised textiles

The silk threads of spiders have been a focus of research for a long time. They are extremely light, tear-resistant and elastic at the same time. Spider silk can absorb three times more energy than Kevlar before it tears.[108] It was possible to decipher the gene sequence for the production of silk proteins and to have them produced by E. coli bacteria. The biotechnically obtained powdered silk proteins have amazing properties and can be processed into different applications. For example, they are biocompatible and well-tolerated, so they can be used to make transparent wound dressings, through which the healing process can be observed, or coatings for implants.[109]

The actual biomimetics is only used in the spinning process. The conventional method of making sutures by extrusion is unsuitable for the silk proteins because the proteins cannot be properly aligned. For this reason, the spinning apparatus of the spider consisting of spinning gland, spinning channel and spinning wart had to be technically abstracted and replicated. In the biomimetic spinning process, the spinning channel is simulated by

[106] Cf. Gäbler, J., Kusumah, I. and Pleger, S. (2007).
[107] Cf. BIOKON (2014b).
[108] Cf. Scheibel, T. (2009), pp. 23 - 25.
[109] Cf. Dostert, E. (2017).

ion-exchange channels, and a pull mechanism provides proper protein alignment to actually spin silk proteins.[110]

AMSilk GmbH near Munich is a spin-off from the Technical University of Munich and manufactures these silk biopolymers. They are marketed under the label Biosteel®. The textile organic fibres are biocompatible, breathable, very robust and biodegradable.[111]

Biomimetic product: Biosteel®

Goal	Lightweight, skin-friendly and environmentally friendly textile materials
Biological model	Silk threads of retilarian (e.g. garden spiders)
Functional principle	Silk proteins are spun into extremely tear-resistant, light, elastic threads in the spider gland
Technical implementation	Biotechnological production of a protein suspension; technical linkage of proteins into continuous mono- or multi-filaments
Resource efficiency potential	Material and energy savings in product manufacturing, resource conservation in the disposal phase
Additional benefits	Longer product service life, better wearing comfort, natural material
Stage of development	Prototype

Sportswear manufacturer Adidas launched a running shoe in November 2016 with an upper made from silk biopolymers manufactured by AMSilk.[112] Adidas markets this shoe under Futurecraft Biofabric as an innovation in sporting goods. The company wants to conduct further research into how Biosteel® fibres can be processed on a larger scale in other products.[113]

Another current research project deals with the production of silk fibres from protein contained in whey from cow milk. The researchers make use of the fact that nanofibrils form in a self-organised way under certain environmental conditions. These fibrils are pressed under lateral water jets through a channel and compacted into fibres. The whey protein used forms corresponding nanofibrils of about 2,000 nanometres in length and four to seven nano-

[110] Cf. Scheibel, T. (2009), pp. 23 - 25.
[111] Cf. Amsilk (2017).
[112] Cf. ADIDAS AG (2016).
[113] Cf. Bioökonomie.de (2016).

metres thick under the influence of heat and acid. The researchers see potential for future applications, e.g., in the context of biosensors or self-dissolving wound dressings.[114]

Contribution to resource efficiency: Spider silk polymers are produced biotechnologically, replacing fossil raw materials in product manufacture. It can be assumed that material and energy can be saved in product manufacturing. However, the production process of the biotechnologically manufactured proteins was not compared with a production process of oil-based polymers, so a conclusive statement on resource efficiency in product manufacturing is not possible. It should be emphasised that the fibres of spider silk polymers are biodegradable and thus contribute to resource efficiency in the recovery phase. In addition, it can be assumed that the Biosteel® fibres are very durable, and the running shoes may need to be replaced less frequently, which could lead to an extension of the service life and thus to material savings.

3.3.2 Surface protection and surface function

Surface structures for liquid transport

The Texan horned lizard was the biological model for the development of functional surfaces for passive, directed liquid transport. It can collect fluid on its skin to meet its fluid needs. This is made possible by the special surface structure with capillary channels between their scales. Thus, with the help of the periodically and asymmetrically changing shapes of capillaries, which contract and expand again, they collect the smallest amount of water from moist sand. The condensed water passes through a connection of the capillary channels, which also prevent backflow, through the head region directly into the mouth of the lizard. This directed, passive liquid transport also works against gravity.[115] When technically implemented, such func-

[114] Cf. Kamada, A., Mittal, N., Söderberg, LD; Ingverud, T., Ohm, W., Roth, SV; Lundell, F. and Lendel, C. (2017), pp. 1232 - 1237.

[115] Cf. Comanns, P., Buchberger, G., Buchsbaum, A., Baumgartner, R., Kogler, A., Bauer, S. and Baumgartner, W. (2015).

tional microstructures could improve the distribution of lubricants in bearings or cutting tools and thus reduce wear. For the development of a prototype, the functional surface of the Texan horned lizard could be applied to metallic components by means of laser beam structuring. Other possible applications exist in the development of new sensors, filter systems, oil separators or heat exchangers.[116]

Biomimetic product: BioLas.exe

Goal	Targeted liquid transport on surfaces
Biological model	Scale structure of the Texan horned lizard
Functional principle	Periodically and asymmetrically changing the shape of capillaries that contract and widen again; connection between the capillary channels, which prevents backflow
Technical implementation	Sawtooth-shaped capillary structures by laser structuring into technical surfaces; software for transferring the structures to free-form surfaces
Resource efficiency potential	Material and energy savings in the utilisation phase
Additional benefits	E.g. improvement of the distribution of lubricants in bearings or cutting tools (thereby reducing wear)
Stage of development	Demonstrator, prototype

Contribution to resource efficiency: The even distribution of lubricants on tools can result in savings in the utilisation phase of the tools. Optimised lubricated components have less wear. This is accompanied by the fact that components need to be repaired or replaced less frequently. This is a contribution to saving material in the utilisation phase. Furthermore, the energy consumption in the processing phase is usually lower for well-lubricated components. In this respect, a saving in the utilisation phase can be derived here as well.

Facade paints

Bacterial films, algae and fungi should be prevented from forming and attaching to the outer facade of buildings for aesthetic reasons, but also for the sake of preserving the building fabric. These microorganisms can discolour the facade or attack the building fabric with their metabolic products. These organisms require a moist microclimate for attachment or colonisation. Therefore, it makes sense to use facade paints, where rain or condensation drains as quickly as possible, to provide a fast-drying surface.

[116] Cf. Fraunhofer IPT (2013).

The biological model for a biomimetic facade paint from Sto SE & Co. KGaA was the fog basking beetle whose functional principles are also used in the development of the fog catcher (see below). The special surface structure of the beetle back shell, consisting of hydrophilic mounds and hydrophobic grooves, allows a rapid condensation of the water, followed by rapid drainage in the direction of gravity.[117] This functional principle was technically implemented for the Dryonic® facade paint by a mixture of binders, pigments and fillers. In particular, the fillers with different particle size and surface polarity take a significant influence on the desired effect. In the drying phase, self-assembly of the raw materials used forms a structure of hydrophilic and hydrophobic areas. Due to the rapid drying of the surface, the addition of biocides could be dispensed with.[118]

Biomimetic product: Dryonic®

Goal	Fast drying of exterior facades after rain or dew
Biological model	Micro-structuring the surface of the wing covers of the fog basking beetle
Functional principle	Surface with hydrophilic mounds and water-draining, hydrophobic grooves condenses moisture and drains it off
Technical implementation	Dispersion silicate facade paint with self-organising binder-filler architecture
Resource efficiency potential	Raw material savings in the utilisation phase, material and energy savings in the product manufacturing phase, protection of ecosystem services in the disposal phase
Additional benefits	If necessary, protection of the substrate material (no penetration of moisture into components); CO_2 certificate: CO_2 neutral colour
Stage of development	Product available on the market

Contribution to resource efficiency: The resource efficiency potential of Dryonic® facade paint can only be estimated from the technical data sheet [119]and the manufacturer's specifications. Facades are colonised by bacteria, algae and fungi over time, regardless of the quality of the paint. The biomimetic facade paint offers the potential that – depending on the environmental conditions – the paint needs to be renewed less frequently. This can lead to savings in raw materials in the utilisation phase, since less colour is used overall. A statement about the resource efficiency in product manufacturing compared to other facade paints is only possible with regard to the use of

[117] Cf. Baulinks (2015).
[118] Cf. Fraunhofer IPA (2015).
[119] Cf. Sto (2016).

biocides: Since these are dispensed with, they do not have to be made. This leads to material and energy savings in product manufacturing. In the recovery phase, the avoidance of biocides makes it possible to remove the facade colour in a more environmentally friendly way, which has a positive effect on water resources and biodiversity. Thus, ecosystem services are spared.[120]

Drinking water

Living in central and northern Europe, it is hard to imagine that there are more than a billion people in the world who have no access to clean drinking water. 2.6 billion people live without water supply and a sewage system. In developing countries, in particular, women usually spend several hours a day collecting water.[121] Due to this fact, which is likely to be exacerbated by climate change, a biomimetic water collection for desert regions was developed under the auspices of the Institute of Textile and Fibre Research Denkendorf (ITV). Because even in the desert regions of the world, there is water, but in the form of evening and morning fog. The fog basking beetle is able to collect the water from the fog.[122]

The current developments for so-called fog traps were optimised in a BMBF-funded joint project by the ITV Denkendorf with the help of the biological model. The goal was to collect clean water in notable yields. After analysis of the surface properties of the back shell of the fog basking beetle, the functional principle could be converted into engineered fibres.

[120] Cf. Baulinks (2015).
[121] Cf. Naturefund (2017).
[122] Cf. Granitza, E. (2013).

Biomimetic product: Fog catcher

Goal	Drinking water production in desert areas
Biological model	Micro-structuring the surface of the wing covers of the fog basking beetle
Functional principle	Surface with hydrophilic mounds and water-draining, hydrophobic grooves condenses moisture and drains it off
Technical implementation	Multi-layer, spaced polyester fabric; installation perpendicular to the wind direction; condensed water flows through the channel into the collection container
Resource efficiency potential	Energy and material savings in the utilisation phase
Additional benefits	Provide drinking water in arid regions, increase the quality of life of residents
Stage of development	Successful feasibility tests in the desert, prototype

A number of basic conditions have been set for the technical textiles. It is therefore necessary that they have the largest possible three-dimensional surface, so that a sufficient amount of water condenses. Nevertheless, they must have a low air resistance so that the fog catchers are not destroyed by storms; they also have to be UV-resistant. Layers of fabric, which are constructed of polyester loops, have proven to be particularly suitable. Several layers of this fabric are provided with spacers and stretched like a net in the fog stream. The condensed mist can be drained and collected in canisters. The project developed prototypes capable of collecting approximately three litres of water per day in extremely dry areas and up to ten litres per day in humid areas. The water just has to be filtered and can then be used as drinking water.[123]

Contribution to resource efficiency: The resource efficiency potential of this development is primarily derived from energy and material savings in the utilisation phase of technical textiles for water production. Even if the effort of producing the fog catchers must be considered, this effort is offset by material and energy required to manufacture and use drills, pumps or tank trucks for the construction and operation of wells and water transport facilities. The primary goal of the biomimetic solution is to improve the quality of life of desert inhabitants by supplying them with vital drinking water. The exploitation of resource efficiency potentials is subordinate to this goal. However, it can be assumed that, for the reasons mentioned above, this decentralised solution also makes a significant contribution to resource efficiency.

[123] Cf. ITV (2013), p. 42 et seqq.

3.3.3 Energy efficiency increase

3.3.3.1 Flow optimisation – air medium

The aim of optimising the flow in the air medium is to reduce flow losses in order to increase energy efficiency and, if necessary, reduce noise emissions. The technique draws on both flying organisms (aerodynamic models) as well as biological models from bodies of water (hydrodynamic models).

Axial ventilators

Axial fans are used hundreds of thousands of times in the IT industry as well as in a variety of components or assemblies such as computers or servers for cooling. Due to the constant operation, a constant noise emission is unavoidable, which is often perceived as unpleasant in the workplace. In addition to increasing the efficiency of fan performance, noise reduction is an entrepreneurial development goal during operation. To achieve this goal, Blacknoise GmbH systematically dealt with the biggest sources of noise in fan operation and mitigated these through targeted optimisation.[124] Measurements with special acoustic cameras have shown that stalls are generated specially at the tips of the rotating blades, which produce the main source of noise for typical fans in the form of large air vortices.[125] The most striking features of the newly developed fans are the self-contained loop rotors. During the locomotion of penguins under water, it was recognised that, in nature, large vortices are broken up by irregular body shapes. This results in a large number of smaller vortices, which in total – even from an energetic point of view – prove to be significantly more effective compared to a few large vortices.[126] It is an adaptation, which can be seen, for example, in the fanned out wing tips of large soaring birds.

[124] Cf. Blacknoise (2013).
[125] Cf. Eckardt, M. (2012).
[126] Cf. BIOKON (2015).

Biomimetic product: BionicLoopFan®

Goal	Lower noise and energy-efficient axial fans
Biological model	Swimming phase of penguins, wings of birds; spreading of the wings and shape of soaring birds
Functional principle	Spreading the primary remiges reduces large turbulences, prevents stalling
Technical implementation	Loop-shaped rotor forms a theoretically infinite wing without a stall edge
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Noise reduction
Stage of development	Product available on the market

By transferring these principles to the wing shape of the fans and the associated flow optimisation, Blacknoise claims to have achieved a reduction in noise emissions of 25 to 35 percent compared to high-quality fans of conventional design with the same capacity.

Contribution to resource efficiency: The noise reduction target is an improvement in energy efficiency in the operating phase of up to 30 percent.[127] This is possible due to the improved flow characteristics of the fan.

Centrifugal fans

The thoracic and caudal fins of the humpback whale are the biological models in the development of the centrifugal fan from Ziehl-Abegg.[128] In centrifugal fans for central air conditioning units or for industrial use, the airflow hits the fan blade at different angles depending on the angle of the volume flow. An unfavourable blade geometry generates stalls and reduces efficiency. The whale has similar challenges swimming in the sea and constantly changes the angular position of its pectoral fins while swimming to manoeuvre in the water. Special bulges (tubercles) on the fins help to prevent flow separation.[128] In addition, the stability of the flow is supported by the body shape of the humpback whale, its tubercles and the shape of the fluke (caudal fin).

[127] Cf. Blacknoise (2013).
[128] Cf. Ziehl-Abegg (2016).

Biomimetic product: ZAbluefin

Goal	Quieter and flow-optimised centrifugal fans
Biological model	Bulges on humpback whale's fins optimise pressure distribution and prevent stalling
Functional principle	Adapted angular position of the fins prevents flow losses. Tubercles (golf ball-sized bulges) have additional favourable fluid-mechanical properties
Technical implementation	Favourable flow-optimised angles and bulges were implemented at the leading edge of the fan blade in the form of a corrugated profile
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Noise reduction, reduction of condensate and dirty water input: less corrosion and imbalance
Stage of development	Product available on the market

The developers have modelled the tubercles at the front edge of their new fan blade and implemented it as a corrugated profile. The shape of the fluke in turn was used as a model for a v-shaped contour of the rear fan blade section[129]. This reduces stalling, which makes the fan usable for many different pressure ranges.[130]

Contribution to resource efficiency: According to the manufacturer, the biomimetically optimised form of the fan blades with better flow characteristics leads to energy savings of up to ten percent in the utilisation phase. It can be assumed that the improved flow characteristics expose the fan to less fluctuating pressures, which may result in a reduction in wear. In this case, there would also be a material saving because the components would have to be repaired or replaced less frequently.

Structured surfaces for noise reduction

Many species of owls have developed a specialised plumage that effectively eliminates the aerodynamic noise of their wings, allowing them to hunt and catch their prey silently. Owl wings have three different plumage types with different physical properties. Feathers with hooks at the front of the wing and fringes at the end cause tiny microturbulences to form on the surface of the wings, which improve the adhesion of the airflow.[131] This leads to signif-

[129] Cf. Stocker, F. (2016).
[130] Cf. Der Konstrukteur (2016).
[131] Cf. Schmidt, F. (2012).

icant noise reduction and has already inspired companies in product design.[132, 133] In addition, the down plumage on the surface of the wing also reduces noise.[134] A 3D reprint of the owl wing structure showed that the wind noise could be reduced by ten decibels without affecting the aerodynamics.[135]

Biomimetic product: Optimised rotor blades of wind turbines

Goal	Noise reduction of wind turbines without restrictions of aerodynamics
Biological model	Down on feathers of owls
Functional principle	Structures of down with almost vertical and branched hairs, which can bend in the direction of the flow
Technical implementation	3D-printed fibrous covers, “finlets”, are attached to the edges of the rotor blades
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Noise reduction (minus ten decibels) during operation, higher acceptance of wind turbines
Stage of development	Research work, prototype

The researchers state that the owl’s down feathers can also serve as a model for wind turbine blade design applications to further optimise noise emission reduction and thus increase the acceptance of wind turbines. In addition, it can also be applied to other low-frequency aerodynamic situations, e.g., for the reduction of air noise with open car windows.[136]

Contribution to resource efficiency: It can be assumed that the desired noise emission reduction is accompanied by energy savings, since the flow resistance is reduced overall. However, publications on the research project do not provide information on resource efficiency potentials, which means that no more specific information can be provided.

Flow-optimised rotor blades

The skin of sharks is equipped with so-called placoid scales, which are anchored flexibly in the epidermis of sharks. This flexibility and a groove-shaped microstructure on the scales, the riblet structure, reduce near-surface

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[132] Cf. BIOKON (2014a).

[133] Cf. Schindlbeck, C. (2013).

[134] Cf. Clark, I. A., Daly, C. A., Devenport, W., Alexander, W. N., Peake, N., Jawoeski, J.W. and Glegg, S. (2016), pp. 33 - 54.

[135] Cf. Phys.org (2016).

[136] Cf. Schmidt, F. (2012).

flow resistance. It also prevents marine life such as barnacles and algae from settling permanently and thus increasing the flow resistance.

A transfer of this functional principle to ship hulls should lead, on the one hand, to an improved flow characteristics and, on the other hand, to the prevention of fouling (growth on the ship's hull). A coating with antifouling properties was developed by Vosschemie GmbH in cooperation with Bremen University of Applied Sciences.[137]

Scientific research has long devoted itself to the effects of riblet structures and is also investigating their transfer to other fields of application. In a research project, a prognosis tool for calculating the efficiency increase in the transfer of riblet structures to real manufactured components is to be developed in addition to experimental investigations.[138] An attempt is made to transfer the flow-optimised riblet structures to rotor blades of wind turbines, gas turbines or other components or units that circulate. Examples are surfaces of trains or aircrafts. However, the turbulence behaviour poses difficulties due to the different scaling of surface structures and environmental conditions.

Biomimetic product: Artificial shark skin

Goal	Flow-optimised surfaces of the rotor blades of wind turbines
Biological model	Riblet structure on placoid scales of skin of fast-swimming fish (e.g. sharks)
Functional principle	Fine grooves in the scales (riblet structure) reduce the flow resistance by reducing turbulence
Technical implementation	Abstracted grooves are brought onto the surface of materials by high-rate laser structuring technologies
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Development of a prognosis tool for calculations
Stage of development	Research project, industrial application planned from 2018

Contribution to resource efficiency: The new investigations on the transfer of the riblet structures to circulating components or assemblies suggest that energy can be saved in the utilisation phase. When considering the resource efficiency of Vosschemie GmbH's ship coating, potentials can be identified in different phases of the product life cycle: For example, on the hulls of large

[137] Cf. Kesel, A. and Liedert, R. (2017).
[138] Cf. Jadewelt (2016).

container ships coated with shark skin, up to 70 percent less fouling with algae, barnacles and other marine organisms can be observed. Even a small growth of a few millimetres increases fuel consumption by more than 25 percent.[139] Assuming a fuel requirement of approximately 180 tonnes per day for a medium-sized container ship, e.g., a Panamax class, the fouling results in an additional requirement of at least 15,000 tonnes and additional costs of around five million euros per year.[140] In addition, one growth per ship causes additional emissions of about four million tonnes of CO_2 per year and about 150,000 tonnes of nitrogen oxides and sulphur oxides.[141] Moreover, the non-toxic shark skin replaces the toxic coating of tributyltin hydride (TBTH). This does not have to be produced or disposed of / recycled in a material- and energy-consuming manner. In addition to energy and material savings in product manufacture, the water resources and marine biodiversity as part of ecosystem services and the climate are protected by lower CO_2 and pollutant emissions.[142]

Small wind turbine

With the DualWingGenerator, Festo GmbH & Co. KG has developed a small energy production unit for low wind speeds as part of the Bionic Learning Network. In contrast to conventional small wind turbines, the system uses two counter-oscillating wing pairs instead of rotor blades for energy.[143]

[139] Cf. Brady, R. F. and Singer, I. L. (2000).
[140] Cf. Hellio, C., Marechal, J.-P., Véron, B., Bremer, G., Clare, A. S. and Le Gal, Y. (2004).
[141] Cf. THB (2009).
[142] Cf. Neubert, H.-J. (2010).
[143] Cf. Festo (2017c).

Biomimetic product: DualWingGenerator

Goal	Wind turbine for low wind speeds
Biological model	Wing beat of birds
Functional principle	Coupled swing-turn motion with high stroke amplitude and small turn creates shear
Technical implementation	Reversal of the principle: Small stroke movement and high rotation amplitude; engineered wings are moved by the wind and power a generator
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Utilisation of even low wind speeds, independent adaptation to fluctuating wind speeds
Stage of development	Prototype and successful feasibility study

The principle of the system consists of the reversal of the natural flapping principle: Birds produce the power they need to fly in the air by flapping their wings. By contrast, a stationary system such as the DualWingGenerator can extract the kinetic energy from the airflow. The system consists of two counter-oscillating pairs of wings, which are attached to a centre column. In the wind flow, the wings move up and down. This creates extreme speeds between the wings. The linear stroke of the wings is converted into a rotary motion. An integrated electric generator converts the energy gained into electricity. The DualWingGenerator is self-optimising and can adapt to different wind conditions.

Contribution to resource efficiency: In the field test, it has been shown that the system has a high efficiency at low wind speeds in the range between four and eight m/s.[144] This means that the energy yield is significantly better, especially at lower wind speeds, and thus, the DualWingGenerator contributes to energy efficiency.

3.3.3.2 Optimised energy transfer and storage

Fluid-based heat transfer

In heat transfer processes, it is usually important that a uniform heat transfer over the entire area takes place. For this purpose, serial or parallel channel systems made of highly conductive metals have hitherto been widely used. The aim is to optimise the heat transfer, i.e., to ensure a uniform flow with low pressure drop. In nature, this is achieved, e.g., in the vascular bundles of leaves, in blood vessels or in the branches of the lungs. With the help of

[144] Cf. Pluta, W. (2014).

these biological models, an algorithm was developed at the Fraunhofer Institute for Solar Energy Systems (ISE) with which the branched fractals could be represented and technically implemented (FracTherm®). This algorithm is already used for the application in collectors and other heat exchangers.[145] The advantages of these fractals include the fact that the pump power can be reduced without flow losses, and the heat transfer efficiency can be increased by very close channels.

The cooling of moulds represents a particular challenge in the automotive industry. These are usually three-dimensional components that need to be cooled evenly before they can be further processed. Here the design of a cooling tool based on a three-dimensional FracTherm® algorithm could be effective. Together with the Fraunhofer ISE, Grunewald GmbH & Co. KG investigated how the 2D FracTherm® algorithm can be transferred to 3D in a feasibility study.[146]

Biomimetic product: FracTherm® 3D

Goal	Efficient and needs-based cooling of moulds, uniform flow, lower pressure loss
Biological model	Structure of the blood vessel system, vascular bundles of leaves
Functional principle	Branching of the blood vessels and vascular bundles to ever finer capillaries; flow and pressure remain almost the same
Technical implementation	Geometric algorithm for creating fractal structures; Adaptation to three-dimensional structures
Resource efficiency potential	Energy savings in the utilisation phase
Additional benefits	Reduction of cycle time during component production due to better heat emission
Stage of development	Demonstrator, prototype, market maturity is expected

At the moment, however, difficulties still arise in the exact mathematical description of the algorithm for the transition of the planar flow course into the third dimension. The commercial production of a 3D FracTherm® tool poses even greater challenges for Grunewald GmbH.[147]

Contribution to resource efficiency: Cooling with a 3D FracTherm® cooling tool means that shorter cycle times can be achieved. Thus, the cooling time can be reduced by a better temperature dissipation from 88 to 39 seconds. This increases the efficiency of the cooling tool per cooled component.

[145] Cf. Fraunhofer ISE (2017a).
[146] Cf. Fraunhofer ISE (2017b).
[147] Cf. Beismann, H., Ossendoth, U., Hermann, M. and Grunewald U. (2015), p. 12 et seqq.

A reduction of the energy consumption can thus be represented by the shorter process duration, since the remaining parameters such as component output temperature, component target temperature, component geometry or cooling water temperature remain the same. Furthermore, the pumping power required for the flow through the pressure-optimised, fractal arrangement of the channels is significantly lower. The efficiency of the cooling capacity and thus the efficiency of the cooling tool could be further increased by replacing the previously used stainless steel tubes with aluminium tubes.[148] Whether this material conversion actually leads to an increase in resource efficiency in the life cycle of the cooling tool must be checked on a case-by-case basis. If necessary, the increase in energy efficiency in the utilisation phase is compensated by possible inefficiencies in the product manufacturing or recovery phase.

Surfaces for solar cells

The search for a solution to increase the efficiency of solar cells led researchers from the Karlsruhe Institute of Technology (KIT) to the higher plants. Photovoltaics is similar in principle to plant-driven photosynthesis: Light energy is absorbed and converted into another form of energy. The efficiency depends crucially on how well the light spectrum of the sunlight can be exploited and whether a high absorption performance can be achieved even at different angles of incidence of the incident light. In photovoltaics, the light spectrum of the sunlight that can be exploited is material-dependent and thus limited.

Biomimetic product: Increasing the efficiency of solar cells

Goal	Increasing the efficiency of the light yield in photovoltaics
Biological model	Nanostructured epidermis of petals of higher plants (here rose petals)
Functional principle	High omnidirectional light absorption and antireflection through surface structuring
Technical implementation	Replication of the surface structure and transfer to a transparent adhesive, integration into an organic solar cell
Resource efficiency potential	Increasing energy conversion efficiency, material and energy efficiency in the utilisation phase
Stage of development	Stage of development

Scientists studied the outer epidermis tissue of various plants for their optical properties and, above all, for their anti-reflection effect. It was found that

[148] Cf. Beismann, H., Ossendoth, U., Hermann, M. and Grunewald U. (2015), p. 43 et seqq.

the epidermis of rose petals has special anti-reflection effects with a broad absorption spectrum and high incidence-angle tolerance. These properties are responsible for the fact that despite different light conditions, the petals form strong colour contrasts and thus increase the chance of pollination. A disordered array of densely packed microstructures and apparently randomly placed nanostructures has been discovered on the epidermis. These surface structures were converted into a transparent adhesive, which was integrated into an organic solar cell after curing by UV light.[149, 150]

Contribution to resource efficiency: Due to the integration of the surface structures, the efficiency at normal incidence of light increased by 12 percent (relative increase). At very low incidence angles, the increase in efficiency was even higher. The researchers attribute the increase above all to the excellent direction-independent anti-reflection effect of the replicated epidermis. From the results, it is possible to derive raw material savings during the utilisation phase, since a comparable energy yield can be achieved with fewer solar cells. Furthermore, the increase in efficiency contributes to the efficient generation of energy.

3.3.4 Robotics and signal transmission

Robotics

Robotics is a wide field that includes many applications, e.g. for automation technology, industrial robots, various assistance robots and drones. One or more components of a robot are usually biomimetically optimised or manufactured, whereby a robot system is usually not completely biomimetically designed. Guideline VDI 6222 Part 1 deals with the question of when a biomimetic robot can be referred to and gives a variety of examples of biomimetic applications in robotics.[151] A representative example from the field of human-machine interaction is explained.

[149] Cf. Karlsruhe Institute of Technology (2016).
[150] Cf. BIOKON (2016).
[151] Cf. VDI 6222 Part 1: 2013: -11, p. 3 and p. 24.

Industrial robots are stiff, unyielding, and cannot operate in the same space without danger to humans, so they are separated from the working environment of humans by protective barriers. In the age of Industry 4.0 and increasing digitalisation, it is becoming increasingly interesting to have robots that can interact directly with humans and work together safely. Soft, compliant systems are created for this purpose that combine perception and communication. Here, biomimetics can help to adapt robot technology to humans and thus become intuitive, ergonomic and safe. In a project funded by the BMBF, a trunk-like robotic arm was developed with the two different approaches of BROMMI:TAK, which fulfils the specified requirements.[152]BR BROMMI stands for "Biomimetic trunk kinematics for safe robot applications in human-machine interaction" and TAK for "Tripedal alternate cascade". In addition to the humanoid muscle robot ZAR5 and the cooperating robot with human-machine interface KobotAERGO, the robotic arm BROMMI:TAK is currently further developed by the interdisciplinary junior research group MTI-engAge.[153]

Biomimetic product: BROMMI:TAK

Goal	Highly flexible and safe movement of a robot arm using lightweight construction, minimising risk during interactions
Biological model	Muscular structure of the elephant's trunk
Functional principle	Bone-free muscles allow for continuous curvature and high mobility with simultaneous flexibility
Technical implementation	Several assembled and interlocked single modules; pneumatic muscles, central control and decentralised drive controllers
Resource efficiency potential	Material savings in product manufacturing
Additional benefits	Safe human-machine interaction is possible
Stage of development	Prototype, further development in the MTI-engAge project

The biological model of this robot kinematics is the elephant's trunk, which consists of approximately 40,000 individual muscles that give it great mobility, dexterity and flexibility at the same time. The robot arm is made up of biomimetic muscles that enable it to move in all directions by pushing, pulling and flexing. It is controlled by decentralised drive controllers with a real-time capable embedded computer and integrated image processing.[154]

[152] Cf. Elkmann, N. (2017).
[153] Cf. MTI-engAge (2016).
[154] Cf. Elkmann, N. (2017).

In the context of demographic change, compliant robots can be used to support industrial production as well as home care or life science.

Another compliant robotic arm is the biomimetic handling assistant, which won Festo and Fraunhofer IPA the Deutscher Zukunftspreis in 2010.[155] Here too, the biological model is the elephant's trunk. However, the individual segments of this robot arm are made of plastic in 3D printing, connected to one another via actuators and controlled by compressed air.

Contribution to resource efficiency: In terms of resource efficiency, compliant collaborative robots, despite their lightweight construction, can move large loads, resulting in material savings in the manufacturing phase and energy savings during the utilisation phase. Additional benefits include space savings in the production facility as these robots no longer have to be separated from the human working environment.[156]

Wireless data transmission under water

Marine mammals such as dolphins and whales use sound waves for communication and positioning. Sound propagates much faster under water than in the air. Dolphins can thus communicate over long distances and use echolocation with ultrasound during hunting. They emit quick, clicking sounds that are reflected and focused by the skullcap. Almost all dolphins emit high-frequency sounds between 30 and 150 kilohertz, which are usually very short with a few microseconds. The echo is picked up by the back of the lower jaw, which transmits the sound to the middle and inner ear. Due to the extremely fast nerve conduction, this only takes seven to ten microseconds.

This biological model of sound transmission was technically implemented in the development of an underwater modem for wireless data transmission. The information to be transmitted is not only transmitted by a carrier signal through phase or frequency modulations, but the frequency of the signal is constantly varied and adapted to the environment. The patented process

[155] Cf. German Future Prize (2010).
[156] Cf. Federal Ministry of Education and Research (2011a).

(Sweep-Spread Carrier, S2C) enables fast and secure telemetric transmission of different digital data.[157]

Biomimetic product: Underwater modem S2C series

Goal	Wireless data transmission under water
Biological model	Acoustic communication of dolphins over long distances
Functional principle	Constantly changing sounds to prevent the signal and echo from being superimposed; echo sounding
Technical implementation	Transmission method that avoids typical interferences such as noise and signal interference (Hall and Doppler-resistant)
Resource efficiency potential	Material savings in product manufacture, material savings in the utilisation phase
Additional benefits	Time savings, faster data transmission under water, more stable communication
Stage of development	Product available on the market

These underwater modems are used in probes, underwater robots, environmental monitoring and the off-shore industry. They are insensitive to interference and noise and can be built into underwater data networks. For example, in the German tsunami early warning system, which was tested in the Indian Ocean, special modems provide the data connection between the ground station (up to 6,000 meters deep) and the satellite buoy on the surface.[158]

Contribution to resource efficiency: This results in material savings in product manufacturing per modem, as the biomimetic modems are smaller than conventional ones. In addition, they are not wired, so that the production and laying of cables under water can be completely dispensed with. A further saving of material in the utilisation phase results from the fact that, due to the high transmission ranges, fewer modems per unit area are necessary, so their number can be reduced.

3.4 Inspired by nature – but no biomimetics

Looking into nature has always inspired people to create something new. This applies to industrial applications as well as to architecture, design or art. As explained at the beginning, not everything inspired by nature is biomimetic. Considered strictly according to the criteria for biomimetics, developments that appear biomimetic at first glance may often not be assessed as

[157] See EvoLogics (2017).
[158] Cf. Spiegel Online (2015).

such (Chapter 2.1). For example, many elements of Art Nouveau are inspired by biological models, but there was no abstraction of a functional principle and no technical implementation.[159] It is not always clear whether a development is truly biomimetic. An example of this is the load-bearing pillars in terminal 3 at Stuttgart Airport. They look like trees and are evidently inspired by the structure of the trees. Whether here, too, an abstraction and technical transfer have taken place, cannot be defined without precise information of the planner and architect. For example, trees do not have the function of carrying loads that act on their branches, which is the case of the pillar construction at Stuttgart Airport. According to this consideration, it is biologically inspired analogies, but not biomimetics.

Regardless of whether it is a biomimetic development or not: Biologically inspired developments are essential for innovation and resource efficiency. For this reason, some current examples are inspired by nature and have considerable potential for resource efficiency and a high degree of innovation. Some of them also advertise to be biomimetic developments, but do not or only partially fulfil the standardised criteria.

FRIMO Street Shark

The Street Shark is an automobile that has a functional surface on the hood and roof.[160] The aim was to reduce the flow resistance of the vehicle. This surface was inspired by the shark skin. In cooperation with the company Eschmann Textures, a tool was produced whose surface geometry was taken directly from the skin of a real shark.[161] This blueprint was used as a model for the surface texture. With the help of this model, the artificial shark skin with coating and PU resin can be applied to components. The application is not limited to the automotive industry, but can also be applied to surfaces of trains, aircrafts or ships. This project was honoured in 2014 with the JEC Innovation Award in Atlanta for its innovative technology.[162]

[159] Cf. VDI 6220 Part 1: 2012-12, p. 18.
[160] Cf. FRIMO (2017).
[161] Cf. Eschmann Textures (2017).
[162] Cf. K-Zeitung online (2014).

According to the criteria for biomimetics, it is not a biomimetic product. Although there is a biological model with the shark skin, the functional principle of the surface properties was not analysed, but rather, a direct copy was made. The replica was, however, technically implemented. In this respect, two of the three criteria for biomimetics are met.

Contribution to resource efficiency: The manufacturers state that the innovative surface of the vehicle could reduce the flow resistance of the vehicle. This should ensure savings in fuel consumption in the utilisation phase. The manufacturing process is almost isothermal and has comparatively low maximum process temperatures of less than 100° C, so it is very energy efficient. The application of the surface onto a component is relatively simple and durable by the use of special paints and resins. This can possibly result in a savings because the treated surface must be repaired or replaced less frequently.

Slewing coil positioner AXXO

Pfeifer Seil- und Hebetechnik GmbH has developed an innovative slewing coil positioner for handling rotationally symmetrical loads such as sheet metal coils or wire coils. The support table can rotate vertically. When it rotates 180 degrees, the load turns 90 degrees and is tilted. Only one tool is needed for turning and setting up for use or for positioning for transport.[163] The AXXO won the User Award at the Blechexpo 2015 in the Handling Technology / Robotics category.[164]

The human hand is given as a model for this development, which is both able to stretch towards the ulna and over the back of the hand, as well as to twist laterally.[165] Same as in the previous example, strictly speaking, there is no biomimetic development. It can be assumed that the designers were indeed inspired by the mobility of the hand. However, there was no abstraction of the complex interplay between carpal bones, radius, ulna, and the tendons and muscles involved. A biological functional principle was apparently also not technically implemented, since the AXXO moves on rollers and bearings.

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[163] Cf. Pfeifer (2017).
[164] Cf. MachinenMarkt (2017).
[165] Cf. Finus, F. (2016), pp. 14 - 18.

Here, only the first criterion “biological model” for biomimetic products is fulfilled. The presentation of an outstanding biologically inspired development is not called into question.

Contribution to resource efficiency: Compared to the conventional way of handling sheet metal coils or wire coils, the AXXO only requires a single tool or load carrier. This reduces the cost of materials to a single tool, which saves space in the warehouse as an additional advantage. In addition, this table is more energy efficient in the utilisation phase, since the rotary motion requires only a low motor power, a 400-volt connection and thus less energy to move.

Octobot

Elastic robots have been a focus of robotics research for several years. They can work with people without the risk of injury as collaborative robots. The Octobot is an attempt to create an elastic, autonomous robot without the use of metallic components that can move independently of an external source of electrical energy. Scientists at Harvard University in Cambridge have developed a small 3D-printed, eight-armed robot made of silicone, which uses hydrogen peroxide as a fuel in a catalytic process. The control units were introduced into the silicone during 3D printing. The Octobot can move the arms independently and autonomously for about eight minutes.[166]

The scientists, without even speaking of a biomimetic approach, have been inspired by molluscs and cephalopods that are able to move only with muscles without an endo- or exoskeleton. The goal was clearly the development of autonomous elastic robots.

This forward-looking research project cannot be considered a biomimetic invention. The cephalopods serve only as a biological model, as they are able to move without a skeleton. There was neither an abstraction of the mechanisms of muscular locomotion nor a transfer of these principles into technology.

[166] Pöppe, C. (2017), pp. 22 - 24.

Contribution to resource efficiency: If the production of a self-sufficient robot, for example, could make use of chemical processes (obtained from renewable raw materials) as an energy source, this robot would be more energy-efficient in the utilisation phase than comparable models. Material efficiency in the manufacturing phase can be assumed when metals are dispensed with and, in addition, fewer materials are used through functional integration. This research is still relatively far removed from the market launch, but does reveal appreciable resource-efficiency potential.

These three examples make it clear that looking into nature provides inspirations that can help the progress, protection and preservation of the environment and, with them, resource efficiency. This applies regardless of whether it is biologically inspired concepts or biomimetic developments.

4 BIOMIMETICS AS AN OPPORTUNITY FOR COMPANIES

Biomimetic methods and approaches open up not only large companies – such as Festo or Airbus, which are also involved in the field of biomimetics – but also small and medium-sized enterprises (SMEs) the opportunity to forward-looking innovations and resource savings. Biomimetics can help companies in the areas of products, processes and services to generate competitive advantages. Biomimetics is to be regarded as an additional approach that makes it possible to extend the solution scope for technical issues (Chapter 2.4). However, by no means should established and efficient procedures and design processes be replaced. Due to the increasing complexity of products and technical solutions, new ways of thinking and approaches are needed. Normative guidelines and innovations that demand cleaner and more environmentally friendly technologies also open up opportunities for resource-efficient and sustainable biomimetic innovations. In particular, the implementation of the EU Ecodesign Directive is a possibility here. The aim of the directive is the environmentally friendly design of energy-related products, taking into account the entire life cycle. The existing guidelines should improve the Ecodesign requirements.[167] In addition, existing limit values of the Ecodesign Directive are to be further tightened by 2019. It is precisely here that the biomimetic approach can open up new ways for companies to better fulfil these requirements, due to its relationship to the environment and nature – and thus the potential for more ecological products.

Therefore, the reasons for companies to use biomimetics and generate competitive advantages are manifold:

- Biomimetics enables the more efficient use of resources as well as the eco-friendly design of products and can help to save costs.

- Biomimetics work usually requires interdisciplinary; it opens up new ways of transcending traditional technical boundaries and produces innovations through cooperation.

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[167] **Cf. Federal Environmental Agency (2016).**

- The biological model offers options for the development of potentially sustainable processes or products, as it is evolutionarily tested, ecologically adapted and has low-risk.[168]

- Biomimetic developments have a high marketing value. Due to the nature reference, biomimetics is generally positively received, and the so-called biomimetic promise also reflects a connection to sustainability.[169] During the marketing, the production process of a product can be presented in an interesting and comprehensible manner based on functionality and the biological model.

Many companies are not accustomed to working together with biomimetics or scientists on an interdisciplinary basis. Even if the advantages become apparent, there is often a lack of imagination as to how biomimetics can benefit one's own company and its own products.[170]

Methodical and technical support in product development

Businesses who want to gain access to the biomimetic approach have many opportunities to get an initial overview. Among other things, standards such as VDI guidelines or DIN/ISO standards provide good assistance. Standards are typically created for tried-and-tested processes in product development and process development. However, it is also possible to already establish technical rules when applications are research-oriented and are not yet established in product development, in order to accelerate innovations in terms of technology transfer in a new technology area. In 2007, the VDI began to develop pre-normative guidelines for biomimetics in a project funded by the German Federal Environmental Foundation (DBU).[171] Nine VDI guidelines on biomimetics have now been published (Table 4). They provide information on the process of biomimetics work and the delimitation of biomimetic to conventional products as well as process descriptions on biomimetic areas

[168] Cf. Speck, T., Speck, O., Neinhuis, C. and Bargel, H. (2012), pp. 128 - 129.
[169] Cf. von Gleich, A. (2006), p. 19.
[170] Cf. Banthin, H. (2014), pp. 40 - 41.
[171] Cf. VDI (2013), p. 5.

such as functional biomimetic surfaces, biomimetic robots or biomimetic information processing.

Due to the high international importance of biomimetics, various ISO standards for biomimetics have already been laid down, based on the preparatory work of national standards (overview at ISO[172]).

Table 4: VDI guidelines for biomimetics

VDI guideline	Title	Issue date
6220 Part 1	Biomimetics – Conception and Strategy – Differences between biomimetic and conventional methods/products	2012-12
6221 Part 1	Biomimetics – Biomimetic surfaces	2013-09
6222 Part 1	Biomimetics – Biomimetic robots	2013-11
6223 Part 1	Biomimetics – Biomimetic materials, structures and components	2013-06
6224 Part 1	Biomimetic Optimisation – Application of evolutionary algorithms	2012-06
6224 Part 2	Biomimetic Optimisation – Application of biological growth laws for the structure-mechanical optimisation of technical components	2012-08
6224 Part 3	Biomimetics – Integrated product development process for biomimetic optimisation	2016-04 (draft)
6225 Part 1	Biomimetics – Biomimetic information processing	2012-09
6226 Part 1	Biomimetics – Architecture, civil engineering, industrial design – Basic principles	2015-02

For the **development of new cooperation** between companies, universities and/or research institutes, the Germany-wide biomimetics network BIOKON e. V. and the various state networks (e.g. Baden-Württemberg, Hesse, Bavaria, Bremen, Saarland) serve as the first point of contact.[173] The competencies of companies, universities, research institutes and other stakeholders are bundled in the biomimetics networks so that the first points of contact for specific questions can be conveyed by the respective branch offices. The networks also provide access to funding initiatives of the federal and state governments.

A regional highlight is the "Competence Atlas of Biomimetics in Hesse", which was commissioned by the Hessian Ministry of Economics, Energy, Transport and Housing of the Bionik-Netzwerk Hessen (biomimetics network in Hesse).[174] In addition to an overview of the biomimetic landscape in Hesse,

[172] Cf. International Organisation for Standardisation (2017).

[173] Cf. Seitz, H. (2013), p. 47 et seq

[174] Cf. Lübbe, K. and Belzer, S. (2015).

there is also a competence matrix and competence profiles with contact persons of those companies in Hesse that concern themselves with biomimetics. The matrix shows in which areas of biomimetics the respective companies are active. In addition, there is an overview of regional and supra-regional networks as well as current support programmes in which companies can apply for financial support for their biomimetic product development.

A support project, as part of the cooperation programme “INTERREG Deutschland-Nederland”, which aims to help **SMEs** especially in the German-Dutch border area, was started in 2016. SMEs in the German-Dutch border area can participate in the project “Biomimetics in SMEs” and work together with biomimetics experts and partner companies. To this end, the project partners developed a concept in which the first phases up to the identification of biomimetic solutions are free of charge. The costs are calculated pro rata only when it comes to the detailed implementation.[175] The project is co-financed by various ministries of both countries and other organisations and is supported by universities, institutes and companies.

Specialised development companies can assist companies with biomimetic product development. They provide systematic approaches to working with the company’s research and development departments to conduct a successful biomimetics project. In the following, two ways of supporting companies are briefly presented.

The five steps that the development company “the biomimetics expert” teach in a biomimetics project are [176]

(1) problem analysis, which shows which functions should be focused on,

(2) screening for suitable biological models,

(3) abstraction as a service,

(4) a creative workshop in which ideas for technical implementation and solution are developed together with the employees of the company, and finally

[175] Cf. Biomimetics in SMEs (2017).
[176] Cf. Banthin, H. (2014), p. 40 et seq.

(5) implementation through prototype, testing and development of the problem solution or innovative product.

Figure 7 is an example of cooperation between development companies and industrial partners.

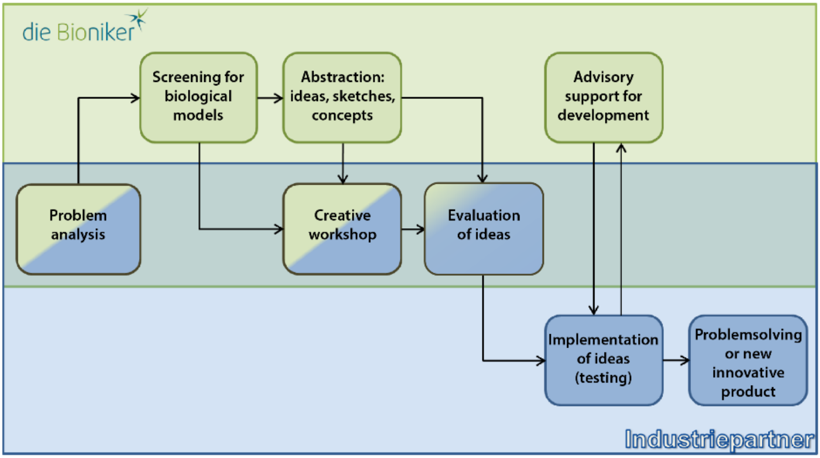

Figure 7: Schematic of an exemplary cooperation between a development company and industry partners[177]

A similar approach is pursued by Pumacy Technologies AG.[178] The innovation management consultants offer companies the opportunity to work together to find a solution through biomimetics and illustrate this with 13 biological models and their potential for technical applications.[179]

If product developers want to examine which biological models are suitable for solving their technical problems, or if they already have better ideas of what a biomimetic solution might look like, there are various **databases** that provide search options. Such databases or software solutions are particularly helpful because biology is now divided into an overwhelming number of different fields. Finding the respective expert or specialist knowledge here is

[177] Banthin, H. (2014), p. 41.
[178] Cf. Pumacy Technologies AG (2017a).
[179] Cf. Pumacy Technologies AG (2017b).

extremely time-consuming.[180] The Fraunhofer Institute for Industrial Engineering IAO has developed a database-supported technology-biology dictionary – BIOPS: Biology Inspired Problem Solving – whose demo version is available free of charge.[181] In order to find proposals for a technical question, the questions can be entered in a search box with English keywords. The user then receives a selection of possible biological models whose functional principles could match the technical problem. In a further step, either suitable publications on this topic are displayed or reference is made to other databases in which corresponding searches can be performed (Table 5).

The databases available so far require a lot of time for setting up, updating and maintenance, as well as experienced employees who take care of it. There are also some databases that are not widely available and are only used in-house. For this reason, there is currently an effort at the ISO level in ISO/TC 266, WG 4, to develop a so-called "knowledge infrastructure of biomimetics" that is easier to use and is freely available. Under Japanese leadership, an ontology-based thesaurus will be developed in the coming years to find analogies in nature.[182]

Table 5: Databases for searching for biological models

Database	URL	Description
BIOPS®, Fraunhofer IAO	www.greentechxchange.com/biops/demo.cgi	Search for analogies
BioPat, Fraunhofer IAO	www.iao.fraunhofer.de/lang-de/ueber-uns/presse-und-medien/336-biopat.html	Fraunhofer internal database: Services
AskNature, Biomimicry Institute, Montana USA	https://asknature.org/	Search for technical solutions and biological models
ScienceDaily, LLC, Maryland USA	www.sciencedaily.com	Search for publications
Freepatentsonline	www.freepatentsonline.com	Patent search

The largest difficulty with the database-driven search for suitable biological models to solve technical problems is that users must have solid scientific knowledge. The assessment of whether the biological model found has functional principles from which the solutions sought can be derived is sometimes very complex and does not necessarily reveal itself at first glance. For this reason, the BIOPS® database has been further developed by employees

[180] Cf. Bertling, J. (2014), p. 159.
[181] Cf. BIOPS® (2017).
[182] Cf. International Organisation for Standardisation (2017).

of the Fraunhofer IAO into the internally used BioPat® software. The software finds biological operating principles and also supports the transfer of these to the technical solutions.[183] However, since this software solution usually requires previous scientific knowledge, Fraunhofer IAO also offers biomimetics potential analysis as a service. For this purpose, the handling of the software, an analysis of the technical orientation and the core competencies of the company, as well as different workshops, are used to generate biomimetic solutions in cooperation with the companies up to process optimisation and product development.[184]

Biomimetics as a building block for innovation – three company examples

Festo AG & Co. KG is a control and automation technology company employing around 18,700 people worldwide. In 2006, the company founded the "Bionic Learning Network" as a development platform for innovative technologies and manufacturing processes.[185] The goal is to develop new, biologically inspired, creative ideas and solutions within a core team together with partners from universities and companies, which help to promote control and automation technology. The aim is to develop and optimise new products and applications for Festo's customers. Another goal is to get young people excited about technology biomimetics and to find new talents for the company. This includes Festo Didactic as a service provider for technical education.[186]

A biomimetic project takes about a year at Festo. The innovations are regularly presented at the Hanover Fair. Components of the developed biomimetic solutions are then optionally implemented in production with customers.[187] In 2010, Festo and the Fraunhofer Institute for Production Engineering and Automation (IPA) won the Deutscher Zukunftspreis for the development of a biomimetic handling assistant.[188] Inspired by the inner structure of the elephant's trunk, this assistant is constructed from compliant materials and operated with compressed air. The gripper is a tripartite "hand" that

[183] Cf. Fraunhofer IAO (2017a).
[184] Cf. Fraunhofer IAO (2017b).
[185] Cf. Festo (2017a).
[186] Cf. Festo (2017b).
[187] Cf. Wolfangel, E. (2016).
[188] Cf. German Future Prize (2010).

works according to the FinRay® effect. This form of soft robotics allows it to work directly with people without the risk of injury. For Festo, biomimetics is a driver of innovation and competitive advantages, but also has a high profile and image.

Similar to Festo, **Airbus** is also planning to strengthen the use of biomimetics as inspiration. The aircraft manufacturer is particularly interested in using lightweight construction through biomimetic methods in combination with additive methods.[189] To this end, the company has set up an internal network to hold conferences, competitions and workshops in order to network biomimetics activities throughout the company and to create synergies.[190] Internal knowledge of biomimetics across the Airbus Group is further developed with biomimetics experts from academia, other networks and research institutes. Among others, Airbus is also working together with Pumacy Technologies AG. Airbus considers this cross-functional and cross-company exchange to be an increasingly important component of its innovation culture. A biomimetic Airbus Concept Plane has been created in this way that shows what an intelligent fuselage, innovative engines or cabin components could look like. The goal is to develop aircrafts that will enable more efficient and environmentally friendly flying.[191]

An SME that also uses biomimetics as an essential component is **sachs engineering GmbH** .[192] The engineering firm for product development, CAD design and FEM calculation uses the biomimetic topology optimisations computer-aided optimisation (CAO) and Soft Kill Option (SKO) for material-efficient lightweight construction solutions in many industries. However, the focus is on the automotive industry. Here, it is possible to achieve weight savings of more than 22 percent for different components – from the connecting rod to the engine mount to the wheel hub – with the same or better stability.[193]

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[189] Cf. Kaiser, O. S., Krauss, O., Seitz, H. and Kirmes, S. (2016), pp. 34 - 35.
[190] Cf. Flugrevue (2014).
[191] Cf. Sander, P. and Hollermann, M. (2014), pp. 42 - 43.
[192] Cf. sachs engineering (2017).
[193] Cf. Sachs, W. (2016), pp. 164-165.

5 CONCLUSION

Biomimetics opens up enormous opportunities for resource efficiency. Biomimetic solutions can offer promising alternatives especially when it comes to the EU requirements for more environmentally friendly product design of energy-related products within the framework of the Ecodesign Directive. In addition to increasing energy efficiency, biomimetic solutions can also contribute to increasing material efficiency.

On the basis of the available literature, resource efficiency potentials of biomimetic solutions could be evaluated qualitatively and retrospectively on the existing products and solutions. The greatest lever for increasing the resource efficiency of products lies in the planning and design of products in the product development process. Biomimetics can make a significant contribution to this. This lever must be used more effectively in future and to create incentives for companies.

Businesses will then always have quick and easy access to biomimetics when already established biomimetic methods or products can be used. When using biomimetic methods, the original process of biomimetics work does not have to be run through every development. This applies in particular to evolutionary algorithms or methods of biomimetic lightweight construction.

Unlike SMEs, it is easier for large companies, which usually have larger development departments, to integrate biomimetics in addition to traditional product development methods. A certain number of development staff with an interdisciplinary focus, equipped with a sufficient development budget, are available here for innovative development tasks. Often, larger companies also have enough development lead to develop promising approaches.

SMEs, in particular, have to weigh up costs, effort and benefits. A biomimetic solution is always interesting when the solutions that are achieved with traditional approaches bring no further or only limited benefits. However, biomimetics, like all other innovation methods, offers no guarantee to success.

For SMEs, there are a variety of ways to gain access to working with biomimetics. Nevertheless, it became clear that various measures are needed to exploit the potential of biomimetics in the future for innovative and resource-efficient products. An essential building block is the interdisciplinary education of young people in teaching and studies. Especially in the scientific discipline of biomimetics, it shows how important it is to include all the necessary methods, to bring together key competences to solve problems and to work together across professional boundaries. The acquisition of these interdisciplinary skills must be part of the education of the next generation.

Beyond the entrepreneurial aspects, strategic research funding plays an important role in establishing biomimetics as an innovation method in the corporate environment:

- Basic biomimetic research to describe the potential of natural principles for technical applications,
- Research on efficient processes for the preparation of complex biomimetic structures,
- Interdisciplinary collaborative research involving SMEs with universities and research institutes for the production of innovative, economical biomimetic products and methods, and last but not least
- Investigations and recommendations on how to integrate resource efficiency as an intrinsic component over the entire product life cycle into biomimetics work.

PART 2: EXPERT DISCUSSION

6 PROGRAMME OF THE EXPERT TALK "RESOURCE EFFICIENCY THROUGH BIOMIMETICS"

Berlin, February 9, 2017

Moderation: Dr. Martin Vogt (Managing Director of VDI Zentrum Ressourceneffizienz GmbH)

TOP 1: Welcome and introductory session

TOP 2: Presentation: Biomimetics as a building block for a resource-efficient economy, Dr. Rainer Erb (BIOKON e.V., Berlin)

TOP 3: Presentation: Resource efficiency through biomimetics – results of a brief analysis of VDI ZRE, Dr. Heike Seitz (VDI Technologiezentrum GmbH, Düsseldorf)

TOP 4: Presentation: Biomimetics as an innovation strategy for efficient and consistent solutions, Dr. Jürgen Bertling (Fraunhofer UMSICHT, Oberhausen)

TOP 5: Moderated discussion about the presentations

TOP 6: Presentation: Facilitate the access of companies to biomimetics, Markus Hollermann (Altran Deutschland SAS & Co. KG, Hamburg), represented by Dr. Rainer Erb (BIOKON eV, Berlin)

TOP 7: Presentation: Near-surface temperature control – with biomimetic tools for more efficiency, Ulrich Grunewald (Grunewald GmbH & Co. KG, Bocholt)

TOP 8: Presentation: StoColor Dryonic – Biomimetics solution for dry facades, Uwe Brühl (Sto SE & Co. KGaA, Stühlingen), represented by Dr. Christian Schaller (Pfinder KG, Böblingen)

TOP 9: Presentation: Synergetic product properties through biomimetic vault structuring process, Prof. Frank Mirtsch (Dr. Mirtsch Wölbstrukturierung GmbH, Berlin)

TOP 10: Moderated discussion and concluding discussion

TOP 11: Summary and Outlook

7 DOCUMENTATION OF THE EXPERT DISCUSSION

On February 9, 2017, a technical discussion on “Resource Efficiency through Biomimetics” took place in Berlin with 24 participants from research, industry, government and professional networks. The VDI Zentrum Ressourceneffizienz GmbH invited to the technical discussion. Discussion blocks looked at the role of resource efficiency in biomimetic products and processes. In addition to questions about the potential of biomimetics for resource efficiency in the individual life cycle phases, the implementation of resource-efficient biomimetic solutions in practice in SMEs – especially in the context of the product development process – was the focus of discussion. Moreover, barriers that discouraged companies from using biomimetics as an innovation and efficiency method were discussed.

7.1 Potentials of biomimetics for resource efficiency

The participants agree that biomimetic or bio-inspired solutions can offer great potential in terms of saving natural resources. This is underpinned by many practical examples. For example, the antifouling properties of an artificial shark skin paint on container ships could reduce the consumption of fossil fuels in the utilisation phase by 40 percent. However, a commercial coating is currently available only for smaller vessels and not yet applicable for coating large areas on container ships. The design routines for lightweight construction products based on biological models that have already been established in the automotive and aircraft industries also lead to a reduction in the weight of the product and thus to a reduction in the use of fossil fuels in the utilisation phase. Examples of design routines are the ELiSE method or the biomimetic methods for structure optimisation.

In the majority of cases, biomimetic solutions are based on individual or partial aspects of products, e.g., surface or structural properties. These solutions have proven to have outstanding effects especially with respect to the performance characteristics of products, which often also contribute to increasing resource efficiency. This is shown, for example, by a biomimetic self-sharpening blade, which now has twice the service life. When determining the material (MIPS[194] analyses) and primary energy expenditure (CED[195] analyses), the water consumption (waterfootprint[196] analyses) or the environmental impacts (life cycle assessments [197]) of individually selected biomimetic products as part of the sustainability assessments within the BIONA funding measure of the BMBF, individual resource efficiency indicators often performed better compared to conventional products. The exception was a design object in the form of a chair, which was manufactured according to the biological model of cell structures in the laser sintering process in plastic design. This was not as resource-efficient as the classic injection moulding process. The reviews of the biomimetic products presented in the expert discussion were only carried out through an analysis of individual resource efficiency indicators, e.g., CED or MIPS and not based on the complete resource efficiency indicator set. Thus, robust quantified data was not available to assess the efficient use of all resource categories in the biomimetic product analyses presented.

Participants, however, estimate the resource-efficiency potential of biological models to be far greater than has been previously exploited. The reduction of biological solutions to individual or partial aspects of products does not do justice to the potentials and possibilities of biological processes and principles. Nature's consistency strategies such as solar economics, circularity, modularity, multifunctionality, self-organisation, cooperation and dynamic adaptivity bear enormous resource-efficiency potential that cannot yet be quantified. The physical and/or chemical processes and basic principles underlying these strategies must be decoded and understood in the future so that they can be transferred into technical solutions. This can lead to innovations or even paradigm shifts in production processes and process chains – even for conventional production processes that have been established over many years. To achieve this, much effort is still needed in basic research and development work. In addition to the resource efficiency aspects, other aspects such as cost-effectiveness, quality assurance and occupational safety must be taken into account. For this, public funding is essential, both in the

[194] MIPS: Material input per service unit.
[195] CED: Cumulative energy demand (according to VDI 4600: 2012-01).
[196] Cf. Hoekstra, A. Y., Chapagain, A.K., Aldaya, M. M. and Mekonnen, M. M. (2011).
[197] Cf. DIN EN ISO 14044.

field of basic research and in the field of application-oriented innovation research. Particularly in application-oriented research, it is necessary to involve companies – especially SMEs – in research networks and cooperation.

The participants see another opportunity for resource-efficient biomimetic solutions in changing legal framework conditions, as provided for in EU's new circular economy package. The regulations and requirements for products on aspects such as reparability, service life and recyclability anchored therein demand and promote the development of optimised and innovative technical solutions. In this way, customer requirements can be directed towards resource efficiency in terms of regulatory policy and a culture of innovation in companies can be stimulated. Biomimetics can provide answers to these regulative requirements.

7.2 Biomimetics and resource efficiency in SMEs

Resource efficiency measures can lead to significant cost savings in companies and are therefore increasingly the focus of corporate strategies in SMEs. During the expert discussion, the question arose as to whether the development of biomimetic products or processes would increasingly be integrated into the strategic orientation of companies.

From the experiences of the participating company representatives, the criteria of price, quality, innovation of products and delivery dates that can be achieved at short notice are usually the focus of corporate strategy. These criteria contribute significantly to the competitiveness of companies. It is irrelevant whether the products offered are biomimetic or conventional. For instance, customer inquiries about biomimetic solutions make up less than five percent of all requests. Thus, there is currently no market pull for biomimetic solutions, since the innovation and resource-saving potential of biomimetics is not yet sufficiently well-known in many companies.

Once product development is familiar with biomimetic solutions, they are generally considered to be a valuable way of expanding the solution scope, as biomimetics is often associated with a high potential for innovation, even if does not always offer the best solution for a specific product or a particular process. Company-internal problems can be discussed with the input of external biomimetics experts. According to experience, interdisciplinary cooperation between the employees is strengthened, and their creativity stimulated in identifying new connections between nature and technology. Thus biomimetics is a means and a tool to expand the company horizon in product development. Whether this creative examination of biological models also leads to marketable biomimetic products or processes depends crucially on other corporate strategy criteria, since the conversion to biomimetic processes is associated with a high entrepreneurial risk. Nevertheless, the biomimetic approach is seen as a valuable addition to the product development process, which can also become a routine component in further developmental processes. Even conventionally implemented manufacturing processes can learn from the natural processes.

If a company strategically anchors the development and implementation of biomimetic solutions, this is primarily due to a visionary concern of corporate governance. The development of biomimetic products can take a long time from idea to market penetration and can last up to ten years. A challenge in this context is the long development time due to complex issues, the identification of the appropriate biological model, interdisciplinary coordination processes in the development team, the integration and, if necessary, adaptation of upstream or downstream conventional production technologies and the associated cost and time intensity. Unlike some large companies that have a biomimetic development department, SMEs need to tackle the challenges with fewer human and financial resources. Federal funding programmes such as the ZIM programme (Zentrales Innovationsprogramm Mittelstand – Central Innovation Programme for SMEs) also make a valuable contribution to the development of biomimetic products and processes. For the development of production-ready software solutions, e.g., for mapping biological processes and principles, the financial resources from a ZIM funding were too low in one example case.

In summary, participants found that linking resource efficiency with biomimetics, and thus developing resource-efficient biomimetic products and processes, presented a great opportunity for companies to meet the future legal framework, market requirements and requirements of a resource-efficient economy. For this purpose, resource efficiency aspects must be included in the specification sheets or in the goal-setting of biomimetic development processes. One suggestion is to extend the resource efficiency measures and strategy table from the VDI Guidelines VDI 4800 Part 1 and VDI 4801 for biomimetic solutions. A list of biomimetic strategies cannot replace intensive collaboration with experts to identify specific biological solutions for individual business-related issues. However, such an overview provides impetus and food for thought to companies considering biomimetics for further innovation or as another innovation method.

In addition to the desire for support measures or strategies for basic and applied research, the participants see a great opportunity in the targeted promotion of young talent. Teaching biological, engineering and systemic basic knowledge and stimulating thinking and creativity processes are of particular importance. Tertiary education has made tremendous progress in recent years, especially by anchoring biomimetics in the technical university programmes in Bocholt and Bremen, and by integrating the subject of resource efficiency into lecture modules of various disciplines. The training activities around biomimetics, sustainability and resource efficiency are supported by target-group-specific information offers. Currently, the BMUB-funded campaign “green up your future” deals with the education of young people about green professions and sustainable approaches of and in companies.

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Im Auftrag des:
Bundesministerium
für Umwelt, Naturschutz,
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