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To cite this article: Olga Speck *et al* 2017 *Bioinspir. Biomim.* **12** 011004

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Bioinspiration & Biomimetics

CrossMark

RECEIVED
3 February 2016

REVISED
16 August 2016

ACCEPTED FOR PUBLICATION
21 September 2016

PUBLISHED
24 January 2017

OPENACCESS
22 February 2017

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TOPICAL REVIEW

Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments

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Keywords: sustainability, decision tree, descriptive/normative/emotional content, supervised learning, bio-inspiration, biomimetics, biomimicry

Supplementary material for this article is available online

Abstract

Over the last few decades, the systematic approach of knowledge transfer from biological concept generators to technical applications has received increasing attention, particularly because marketable bio-derived developments are often described as sustainable. The objective of this paper is to rationalize and refine the discussion about bio-derived developments also with respect to sustainability by taking descriptive, normative and emotional aspects into consideration. In the framework of supervised learning, a dataset of 70 biology-derived and technology-derived developments characterised by 9 different attributes together with their respective values and assigned to one of 17 classes was created. On the basis of the dataset a decision tree was generated which can be used as a straightforward classification tool to identify biology-derived and technology-derived developments. The validation of the applied learning procedure achieved an average accuracy of 90.0%. Additional extraordinary qualities of technical applications are generally discussed by means of selected biology-derived and technology-derived examples with reference to normative (contribution to sustainability) and emotional aspects (aesthetics and symbolic character). In the context of a case study from the building sector, all aspects are critically discussed.

1. Introduction

1.1. Key terms

Over the past few years numerous and diverse terms have appeared, all of which describe the inspiratory flow of ideas from nature to technical solutions: biomimetics, bionics, bio-inspiration, biomimicry, biomimetic promise, nature-based solutions and many more. Given the quantity of academic and popular literature on this subject and with respect to the huge number of authors very different and sometimes contrary explanations can be found. The situation is further complicated because the terms have appeared from various scientific disciplines, whereby each discipline has its own language, way of thinking and methodological approaches. Another source of confusion is the translation of the terms into other languages. A closer look, however, reveals that differences can indeed be found with regard to, for example, the selected role model, the quality of knowledge transfer, the respective function and the developmental status. Here, we have to take into consideration that besides the descriptive content each term also possesses normative and emotional aspects. Especially noteworthy is the assumption that living nature may serve as concept generator to meet the challenges of sustainable development in terms of social, environmental and economic goals. Thus, to rationalize and refine the discussion, we need to define these key terms precisely. Clarifying the meaning of terms, especially in an interdisciplinary field of research and development, might help to eliminate misunderstandings in daily work.

In 1957, the American engineer and physicist Otto Herbert Schmitt coined the term 'biomimetics' as a biological approach to engineering in contrast to 'biophysics', which describes the engineering/physical approach to biology [39, 56, 66]. The term 'biomimetics' first appeared in 1974 in Webster's Dictionary defined as the study of the formation, structure, or

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function of biological materials, mechanisms and processes in order to synthesize artificial products that mimic natural ones [66]. This description can be found unchanged today in Merriem-Webster's online Dictionary [82]. In 1958, the American medical doctor Jack E. Steele introduced the word 'bionics' in terms of copying functions from nature during his time at the Aerospace Medical Research Lab. Officially, 'bionics' was used in 1960 as the title of a meeting at the Wright-Patterson Air Force Base in Dayton [66]. After his retirement, Steele studied engineering and, in 1977, wrote a master's thesis with the title 'Bionic Design of Intelligent Systems' [83]. In contrast to 'biomimetics' and 'bionics', the term 'bio-inspiration' is more encompassing. The chemist Whitesides [81] defined 'bio-inspiration' as '*using phenomena in biology to stimulate research in non-biological science and technology*'. He further stated that abstracting simplified versions of a living creature means taking inspiration from its capabilities and mimicking some of its functionality by using simplified and probably different mechanisms [81]. The American forestry scientist Janine M. Benyus popularized the term 'biomimicry' by publishing the book 'Biomimicry—Innovation Inspired by Nature' [11] and by founding the 'Biomimicry Institute'. In general 'biomimicry' means learning from natural world by imitating or taking inspiration from nature's designs and processes to solve human problems. Furthermore, there is a particular emphasis on sustainable design ideas emulated from nature. '*Biomimicry uses an ecological standard to judge the 'rightness' of our innovations. After* 3.8 *billion years of evolution, nature has learned: What works. What is appropriate. What lasts.*' [11]. The German biologist Arnim von Gleich has coined the term 'biomimetic promise', which indicates that, precisely because of the inspiratory flow from biology to technical products, biomimetic solutions have the specific potential to contribute to sustainable technological development [76–79]. The European Commission, the International Union for Conservation of Nature and other political organisations have claimed the so-called 'nature-based solutions'. An explanation is written on the official EU-Website [84]: '*In this context, we define nature-based solutions to societal challenges as solutions that are inspired or supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience…*' This definition is in the context of the EU R&I agenda for Nature-Based Solutions and Re-Naturing Cities and therefore covers a broad thematic spectrum of societal challenges to be solved: '*These nature-based solutions provide sustainable, cost-effective, multi-purpose and flexible alternatives for various objectives. Working with nature, rather than against it, can further pave the way towards a more resource efficient, competitive and greener economy. It can also help to create new jobs and economic growth, through the manufacture and delivery of new products and services, which enhance the natural capital rather than deplete it*' [84].

1.2. Technical rules and standards

Against the background of a wide range of terms with partly unclear, contradictory or synonymous meanings and the request for methodological approaches how to learn from biology for technology, the Association of German Engineers (VDI) and International Organization of Standardization (ISO) have developed technical rules and standards with the intention of raising the profile of biomimetics. Among others, the guidelines set target on the description of state of the art, harmonisation of terminology and technical language, and assistance in the practical realisation of technical applications. Therefore, they can be seen as a valuable contribution to the definition and developmental approach of bio-derived solutions. Recently, a total of nine VDI technical rules, available in German and English, have been worked out by experts focusing on various areas of application: concept and strategy [67], biomimetic surfaces [68], biomimetic robots [69], biomimetic materials, structures and components [70], biomimetic optimization [71–73], biomimetic information processing [74] and basic principles of architecture, civil engineering and industrial design in the framework of biomimetics [75]. In this context, various definitions are available, such as that for 'biomimetics' as being a combination of biology and technology with the goal of solving technical problems through the abstraction, transfer and application of knowledge gained from biological models [67]. Since 2015, ISO standards in English and French provide several definitions and practical realisation concepts [33, 34]. In the ISO standard [33] 'biomimetics' is defined as an '…*interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution.*', whereas 'bionics' is describes as a '…*technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents.*' Moreover, the terms 'biomimicry' and 'biomimetism' are both defined as '…*philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development* (*social, environmental, and economic*)' [33]. Further technical rules, guidelines and standards addressing additional fields of development are planned, if experts from interested circles are willing to work together in an honorary capacity. A commenting procedure guarantees the opportunity to exert influence by interested public. Because the guidelines are drawn up by numerous international experts working in the respective field, they are of upmost importance for the description of the status quo.

1.3. Topics

Many excellent reviews are available on bio-inspiration and biomimetics focusing on specific topics such as publications and topics [39], the analysis system TRIZ [66], selected bio-inspired solutions in robotics and prosthetics [7] or bio-inspired soft robotics [55], and biological and biomimetic materials [1, 80]. In addition, over recent years important contributions have to be mentioned especially in the field of biologically inspired design (BID) with focus on computational methods and tools [22, 45], healthcare and medicine [38, 65] and the building sector together with architecture [27, 35, 48, 51]. An upcoming topic is the focus on future biomimetic contributions to global challenges [20] and the systematically generation of sustainable products using biomimetics [76–79], or biomimicry as a sustainable design tool [11, 54] and in the framework of bio-inspired design using biological analogies [47]. Moreover, biomimicry's potential role in addressing sustainable building engineering [14, 49, 50] and sustainable architecture [44] has to be mentioned. However, this enumeration of topics and publications could be further complemented because inspiration from living nature has influence on basic and applied sciences in a variety of topics.

1.4. Motivation

The intension of this study, carried out in the framework of the currently running project 'The biomimetic promise: natural solutions as concept generators for sustainable technology development in the construction sector' as a subproject of the CRC-Transregio 141 'Biological Design and Integrative Structures—Analysis, Simulation and Implementation in Architecture', is a contribution to rationalize and refine the discussion about bio-derived and technology-derived developments by taking into account that each of them possesses descriptive, normative and emotional aspects. In this context specific attention has been paid to the role of sustainability.

The first objective of this study is the focus on the descriptive aspect by the provision of a straightforward classification tool to clearly describe, distinguish and identify biology-derived and technology-derived developments. This was achieved by the compilation of a dataset of relevant developments characterized by descriptive attributes with several values. The second objective is a critical reflection of the normative and emotional aspects of bio-derived products as to whether they promise an additional extraordinary quality in terms of sustainability potential or emotional perception. Third, a 'bone like' ceiling is chosen as a case study from the building sector to critically discus the descriptive, normative and emotional aspects.

2. Fields of interest in the interdisciplinary approach

'Nature' and 'culture' constitute a word pair whose interplay has varied through history and has been described by numerous authors [20, 28, 75]. They are often regarded as two discrete opposite sides of a dualism, whereby culture typically denotes everything that is anthropogenic, in contrast to non-man-made 'living nature' (biotic, i.e. plants, animals, fungi, bacteria) and 'non-living nature' (abiotic, i.e. stones, liquids, gases). In this context, we will not contribute here to this exciting discussion about nature and culture but merely highlight the fields of interest with a general focus on the developments derived from the knowledge transfer between natural sciences (e.g. biology, geology), and technology (design and engineering) (figure 1) with a special focus on the building sector.

Fruitful interdisciplinary cooperation is widely recognized to arise substantially from all scientists working both in their own field of expertise and in the transition zone between the disciplines. In general, nature-derived developments are mostly the result of collaborative work and pooled expertise in the field of 'natural sciences' and 'technology'. 'Nature-derived developments' cover all technical solutions derived from natural concept generators, whereas 'bio-derived developments' are solutions gained from living organisms or with their assistance. Moreover, 'geo-derived developments' describe technical solutions having non-living concept generators. 'Technology-derived developments' have no natural models that influence the development of technical solutions, even though they might end up with a natural appearance or a similar function to one found in nature. In this study biology-derived and technology-derived developments are in focus, the discussion about geo-derived developments would be a specific venture.

A particularly interesting challenge in the nature versus culture context is the question as to whether biology-derived applications may contribute to sustainability in general and particularly in the building sector. With a focus on the building sector over the last few years, biologists, chemists, physicists, material scientists, mathematicians, designers, architects and civil engineers have successfully transferred biological design principles such as heterogeneity, anisotropy, hierarchy, multi-functionality and adaptability in architecture [35]. Besides numerous methods used in the creation of sustainable architecture, Pedersen Zari [49, 50], presents the ecosystem biomimicry as a means to either mitigate the cause of climate change that the built environment is responsible for (e.g. CO_2 emissions, land use change), or adapt to the impact of climate change (e.g. increase of temperature and of intense weather events). Buildings in general and cities specifically are key players in sustainability and will

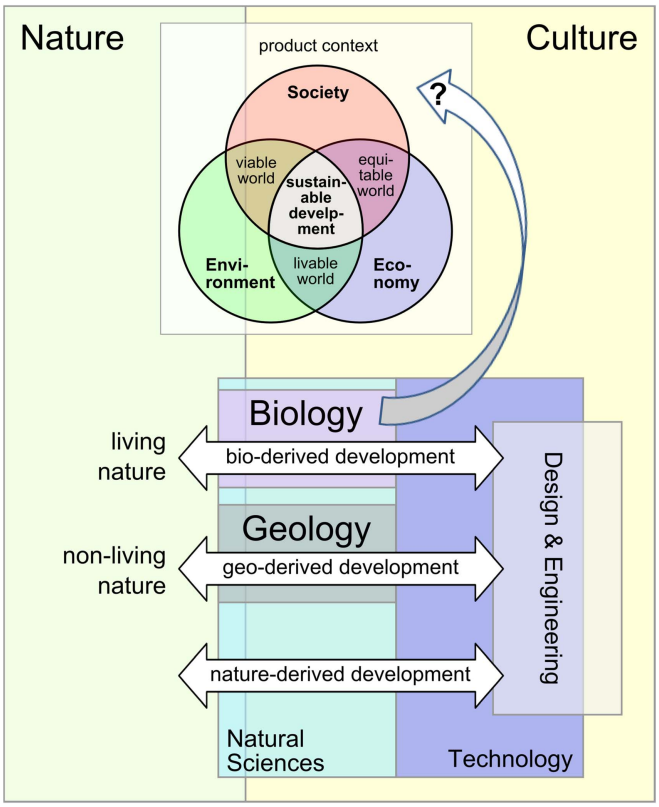

Figure 1. Schematic drawing of key terms and their relationships. The double arrows reflect the knowledge transfer from natural solutions to technological applications and in turn the deeper insights into the functioning of the natural concept generators because of new findings which arise in the course of the developmental approach. Whether bio-derived developments have specific potential to contribute to sustainability in general and, in particular, to design and engineering is a recent subject of discussion.

determine the fate of mankind. Worldwide, cities grow with immense speed: whereas in 1900, only 10% of people lived in cities [13], nowadays more than half of mankind lives in urban surroundings having an ongoing dynamic trend towards urbanization, with 75% of the world population probably living in cities by the 2050s. The respective resource consumption and waste production of cities exceed by far the capabilities of their surrounding environment. The construction industry is a large contributor to CO_2 emissions, with buildings responsible for 40% of the total European energy consumption and a third of CO_2 emissions. At the same time, construction is by far the largest resource consumer. Therefore, cities and the construction sector play a significant role in the fulfilment of the 20/20 targets of the European Union—the reduction of primary energy consumption and CO_2 emissions by 20% and the increase of renewable energy sources as a proportion of total energy to 20% [19, 84]. As one of the major approaches for tackling these challenges, design concepts will play a major role in seizing opportunities offered by future construction projects and mega cities. The ecosystem biomimicry described by Pedersen Zari [49, 50], is one of many approaches to improve sustainability outcomes of architectural design and, therefore, is especially mentioned here, because it is a biomimetic design in terms of mimicking ecosystem functions or ecosystem processes. A list of 22 ecosystem process strategies for built environment, which could be practically related to architectural or urban design, is presented in Pedersen Zari [50].

3. Biology-derived and technology-derived developments

An essential prerequisite for the precise characterisation of biology-derived and technology-derived developments in terms of communalities and differences is the collection of detailed background information. In the case of bio-derived developments, this is ultimately a consequence of the missing specific design language that gives clear information about a possible origin from biology and additional information about the knowledge transfer. In this study background information was gathered by literature research, information derived from technical rules and standards, results from a survey with international scientists, and discussions with experts from the field of bio-inspiration and scientists (supplementary appendix 1).

3.1. Descriptive aspects: definitions, approaches, classification

In the following, we will briefly point out the essential facts of selected biology-derived and technology-

derived developments to describe them in the best possible manner and to make them distinguishable from the others. This is supported by the description of well-known and strong examples. The described examples and many more can be found in the dataset (supplementary appendix 1, table S1).

In total 17 classes are unambiguously defined, whereas four classes belong to the technology-derived developments (technical product, technical product developed in parallel to biology, technical product with natural appearance, and algorithm) and 13 classes belong to the bio-derived developments (biotechnological product, bio-inspired product, biomimetic algorithm, biomimetically optimised product, biomorphic product, functional biomimetic product, structural biomimetic product, functional biomimetic and biomorphic product, structural biomimetic and biomorphic product, functional biomimetic and biotechnological product, structural biomimetic and biotechnological product, functional biomimetic, biomorphic and biotechnological product, structural biomimetic, biomorphic and biotechnological product). There are nine descriptive attributes and their respective values (model, direct use of living organisms, bio-inspiration, application of biomimetic algorithm, transfer of morphology, transfer of principle, natural appearance, same function, and status (supplementary appendix 1)).

In the framework of supervised learning a binary ('dichotomous') decision tree (figure 2) was generated by the ID3 algorithm [53] using the whole dataset as training set (supplementary appendix 1 and 2). The decision tree is a 'flowchart-like' classifier which originates in a root node proceeding down to its leaf nodes (=class names) via internal nodes (=attribute-based tests) and branches (=possible outcomes). The underlying ID3 algorithm starts with the original data set and calculates the entropy and the information gain of all attributes (equations (1) and (2) in supplementary appendix 2). The attribute with the smallest entropy or largest information gain (=splitting function) is the root node and splits the original dataset into subsets. In terms of a recurse approach ID3 splits the respective subsets using remaining attributes.

In order to evaluate the learning procedure, 5 different decision trees (classifiers) were evaluated using the 5-fold cross validation method [42]. Overall, an accuracy of 90.0% was achieved to predict the classes of the test examples correctly. For example, compared to a baseline algorithm which always predicts the most common class of the training set (17.1% accuracy in the 5-fold validation) the used learning procedure performs well. Thus, we can conclude that the provided decision tree using the whole dataset as training set is an accurate model to predict new (unknown) instances. In this context, the provided decision tree is a handy and accurate tool that allows a rapid identification which class a given development belongs to. In biology and medicine such printed or computer-aided identification keys are very common to identify biological entities and diseases, respectively.

3.1.1. Bio-inspired developments

Originally, an inspiration is defined as a sudden idea. If we consider even the transfer of an idea from a biological model into a technical application is a conscious process of creativity, then 'bio-inspired developments' are technical solutions having a biological idea generator [75, 81]. The inspiring idea might be the starting point for additional knowledge transfer, namely, the morphology of biological models leading to 'biomorphic developments', several operating principles that lead to 'biomimetic developments' and/or the 'application of a biomimetic algorithms' resulting in a 'biomimetically optimised product'. Furthermore, various combinations of knowledge transfer gained from one or more biological concept generators are even possible. In any case, a development can at least be mentioned as bio-inspired, when there is persuasive evidence of an existing biological concept generator.

An often controversially discussed example regarding bio-inspiration and knowledge transfer from biology to technology, is the invention of reinforced concrete by the French gardener Joseph Monier in 1867 [17, 33, 67]. Similarities between biological composite materials consisting of fibres with high relative strength embedded in a matrix of ground tissue and the technical composite material with steel reinforcement in cement are obvious with regard to the internal structure and the operating principle. It is a fact that Joseph Lambot already submitted a patent on ferro-cement in 1855. His patents for objects exposed to moisture (boats, water tanks and troughs) were later superseded by patents of Joseph Monier, who early on used reinforced concrete for the production of planter boxes. There are some indications that the gardener Monier was inspired by plant structures. However, in terms of the arrangement of reinforcements he did not overcome empirical findings and therefore never gained an in-depth understanding of the operating principle of reinforced concrete. Taking all facts and indications into account, reinforced concrete can be classified as a bio-inspired product.

A promising research area in engineering is the BID that systematically utilises similarities between nature and design challenges to bring inspiration to designers. In general, BID takes place on basis of visual, conceptual and computational inspiration. First, based on illustrative material of biological concept generators engineering applications with natural appearance may be developed (see also chapter 3.1.5). Second, conceptual inspiration means the creation of design rules or patterns following biological role models. Third, computational inspiration is the possible transfer of algorithms from evolution, natural morphogenesis or others [62]. Menges [45] describes in general the significant differences between computer-aided and computational design in architecture and,

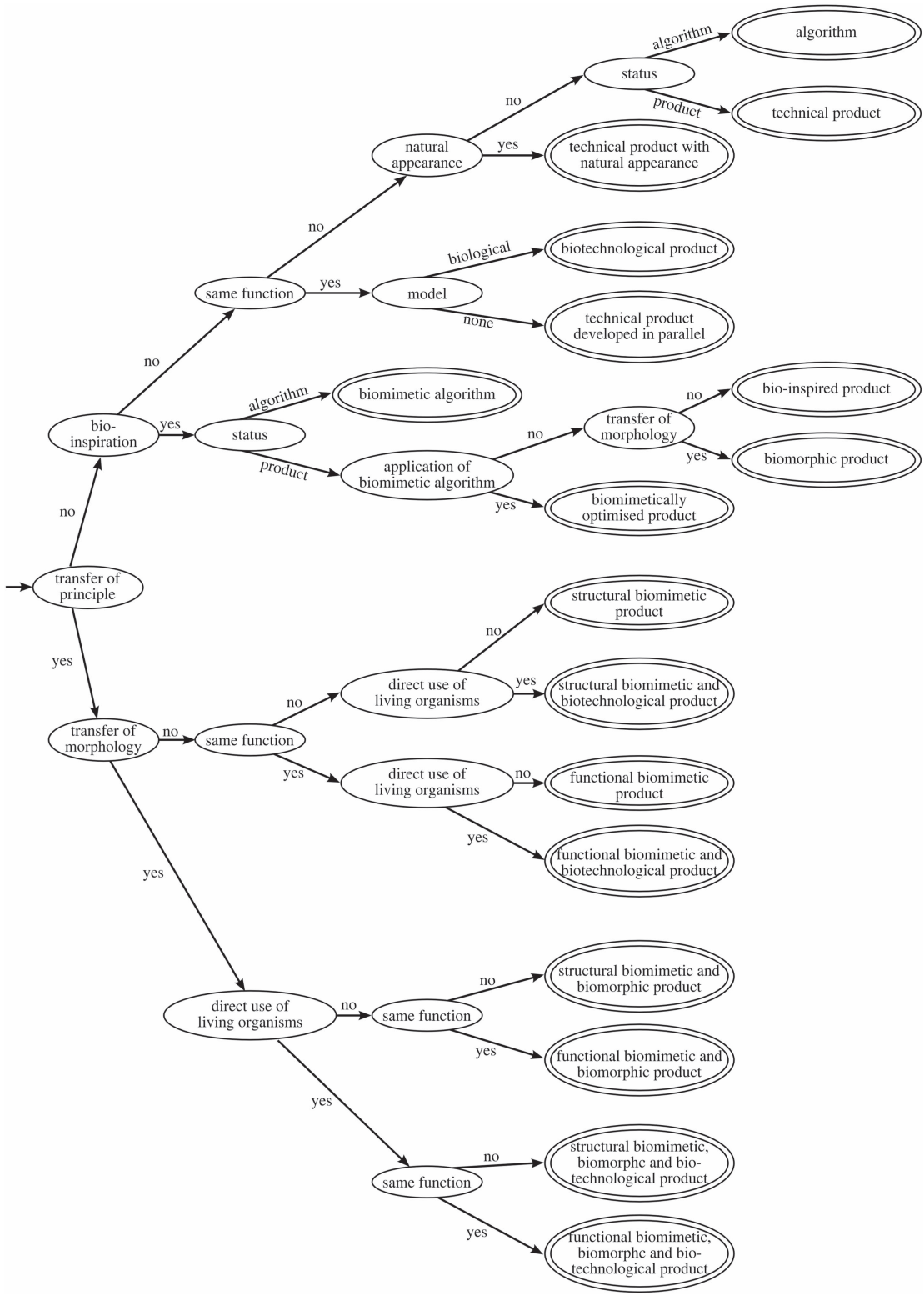

Figure 2. Decision tree generated on the basis of the whole dataset shown in table S1 (supplementary appendix 1) as a straightforward analysis tool to identify various kinds of biology-derived and technology-derived products and algorithms. Each internal node (represented by an oval) tests a nominal attribute, each branch (illustrated by an arrow) represents the outcome of the test and is labelled with the corresponding attribute value, and each leaf node (represented by a double oval) assigns a class. The classification begins at the root node, represented by the attribute 'transfer of principle', because it shows the highest information gain (see table S2, supplementary appendix 2) with reference to all samples $\{1, 2, \ldots, 70\}$.

in particular, introduces morphogenetic and evolutionary computational design as a biomimetic design process. In the cases of conceptual and computational design it is very likely that in addition to a single inspiration also principles, morphology and/or algorithms are transferred resulting in the respective classes. The relationship between BID and sustainable design will be discussed in detail in chapter 3.2.

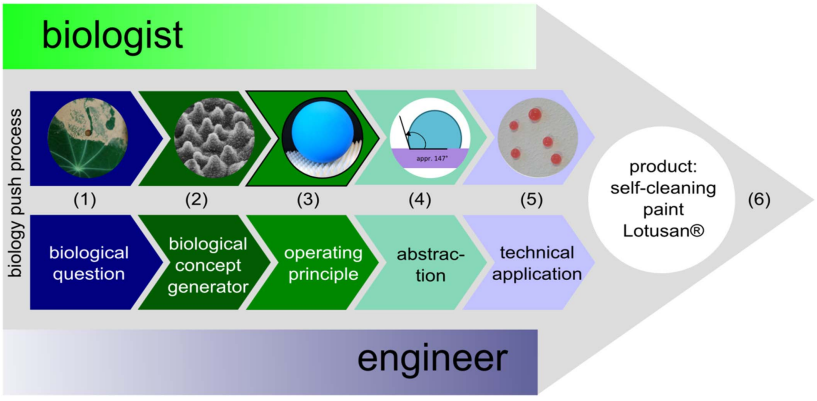

Figure 3. The bottom-up approach (biology push process) of the self-cleaning paint Lotusan®. (1) What is the basis of the self-cleaning effects of plant surfaces in general and of lotus leaves (*Nelumbo nucifera*) in particular?; (2) SEM picture showing a micro- and nano-rough plant surface with wax crystalloids (Photo courtesy of C. Neinhuis, TU Dresden); (3) the functional principle is the minimal contact area between dirt particles and the surface based on a hierarchically micro- and nanostructured and water-repellent surface in combination with water droplets; (4) lotus surfaces show contact angles of approximately 147°; (5) technical applications with this operating principle bear the Lotus-Effect® trademark; (6) the self-cleaning façade paint Lotusan® has been on the market since 1999.

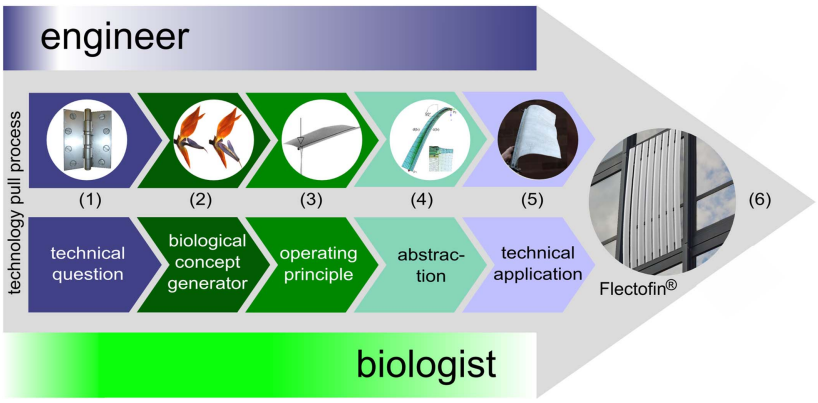

Figure 4. The top-down approach (technology pull process) of the self-adapting façade shading system Flectofin®. (1) Is it possible to find hinge-less kinematics of deployable systems for architectural purposes?; (2) the biological model was the elastic deformation system of the perch of the bird-of-paradise flower; (3) the functional principle is a lateral-torsional buckling; (4) the kinematic structure is simulated with finite element modelling; (5) technical applications consist of one or two laminae and one backbone; (6) closed state of Flectofin® lamellae (translated and reprinted with permission from [52]).

3.1.2. Biomimetic (bionic) developments

In 2014, experts published VDI-Guideline 6220 (2012) [67] dealing with the concept and strategy of 'biomimetics' and differences between biomimetics and conventional methods/products and provided the following definition: '*Biomimetics combines the disciplines of biology and technology with the goal of solving technical problems through the abstraction, transfer, and application of knowledge gained from biological models. Biological models in the sense of this definition are biological processes, materials, structures, functions, organisms, and principles of success as well as the process of evolution itself*'. This definition may also hold true for 'biotechnology' and therefore has to be completed by the statement that, in biomimetics, living organisms are exclusively indirectly (i.e. as concept generator) involved in the production of biomimetic products and the development of biomimetic process engineering.

Two biomimetic approaches are well established, which differ from each other at the starting point for development: starting with a question from biology leads to the biology push process = bottom-up approach (see also figure 3), whereas starting with a question from engineering sciences leads to the technology pull process = top-down approach (see also figure 4). Both approaches result in a 'biomimetic development', i.e. a technical application developed on the basis of the transfer of knowledge (operating principles, manufacturing processes) gained from one or several biological concept generators [60, 67].

During the implementation of functional principles and manufacturing processes found in biological solutions into technical developments ('biomimetics'), new findings arise that, in turn, contribute to a deeper insight into the functioning of the biological concept generators ('reverse biomimetics'). This requires a re-investigation of the biological samples to

achieve a continuous improvement of the technical models of the engineers. In the sense of the heuristic spiral consisting of 'technical biology' (e.g. functional morphology and biomechanics of the biological concept generator), 'biomimetics' and 'reverse biomimetics', the process leads to a considerable gain in understanding of both the biological and the technical systems and to a refinement of the developed technical applications.

Goel *et al* [23] present comparable approaches in BID. The designer's starting point of the solutions-based analogical process is a biological source of interest, followed by the extraction of principles and the subsequent search for human problems which can be solved by the application of the principle. The problem-driven analogical process starts with a problem identified by a designer, goes on with a phase of biological solution search, and the extraction and application of a principle.

A well-known biomimetic product is the façade paint Lotusan® equipped with the self-cleaning Lotus-Effect® developed on the basis of the self-cleaning function found e.g. in the leaves of *Nelumbo nucifera* [9]. Because the biomimetic application has the same function as the biological model, it is called a 'functional biomimetic product'. The development of self-cleaning surfaces bearing the Lotus-Effect® trademark is a typical example of a biology push process (bottom-up approach) in biomimetics [68]. Figure 3 shows a simplified flow chart starting with basic biological research on plant surfaces showing self-cleaning effects. The transferred principle is the minimization of the contact area between adhesives (e.g. dirt particles) and substrate (e.g. surface) based on a hierarchically micro- and nanostructured and water-repellent (superhydrophobic) surface in combination with the surface tension of water [68]. Superhydrophobicity of a surface can be measured by the contact angle between the liquid and the solid surface, which in this case, by definition, has to be larger than 150°. The contact angle of a water drop on a lotus leaf surface is approximately 147°. Lotusan® paint has been on the market since 1999 and has been used for millions of square meters of façade throughout the world [85]. However, the self-cleaning effect in biology and technology occurs under the restriction that water droplets are available to wash off the dirt.

If the biological model and the biomimetic application do not have the same function, as for example in the case of the façade-shading system Flectofin®, they are called 'structural biomimetic products'. Flectofin® is a hinge-less flapping shading system for architectural constructions derived from the deformation principle found in the bird-of-paradise (*Strelitzia reginae*) flower during pollination by birds [41]. Figure 4 shows the stepwise development of Flectofin® in terms of a top-down approach (technology pull process). State-of-technology constructions often consist of separate stiff elements connected with hinges, whereas local hinges are error-prone and require regular and cost-intensive maintenance. Consequently, the starting point of the Flectofin® development was the challenge to find a hinge-less kinematics solution of deployable systems for architectural purposes. The concept generator was the flapping mechanism of the perch of the bird-of-paradise flower which is triggered by the weight of the pollinating bird in order to reach the nectar at the base of the flower. Analyses showed that the model's operating principle is a lateral-torsional buckling, which—in engineering—is well-known as an undesirable failure mode. After several levels of abstraction, the kinetic structure could be simulated with finite element modelling. After optimization of both material and shape of Flectofin®'s laminae and backbone, solutions with a single or double wing have been made available [41]. At EXPO 2012 in Yeosu (South-Korea), the kinematic façade-shading system of the Thematic Pavilion was achieved with modified Flectofin® lamellae [61].

'Biomimetic algorithms' are characterized by biological evolution and processes being available as evolutionary algorithms and complete mathematical formulations in order to optimize technical products and process engineering [71]. Furthermore, computer-based biomimetic optimization tools, such as computer-aided optimization (CAO) derived from the growth rules of trees and the soft kill option (SKO) following the growth rules of bones, modify the shape and topology of components and homogenize the stresses at the component's surface. The subsequent application of these optimization algorithms from the plant kingdom and animal kingdom is a completely unique combination that does not even exist in living nature [72]. The biomimetic design tool ELiSE 3D draws on the shell or skeleton design of marine organisms (e.g. diatoms and radiolarian) to improve large scale technical lightweight structures [73].

The increasing availability of biomimetic algorithms leads to numerous 'biomimetically optimised products'. Famous example are the SKO-optimised frame of the Mercedes-Benz bionic car [89] and the CAO-optimised orthopaedic screw which can withstand 5 million load cycles in contrast to the non-optimised one which fatigue cracks after only 220 000 load cycles [67].

In addition to biomimetics, one often finds the term 'bionics'. The latter is frequently used as a synonym for biomimetics in terms of learning from biology for technical innovations. Specific uses of 'bionics' in medicine or robotics might have their origins in the original focus on electronics. An additional role may have been played by the famous American television series 'The Six Million Dollar Man' and its spin-off 'The Bionic Woman' in which human beings possess advanced bionic prosthetics and implants to confer artificially enhanced skills. Strong examples for the diverse use of the word 'bionics' are the following societies, networks and journals. The 'International

Society of Bionic Engineering' and its '*Journal of Bionic Engineering*', both are located in China. 'BIOKON international—The Biomimetics Association' is a European network and the 'Competence Network Biomimetics' is located in Germany. Over the last few years, bio-inspired and biomimetic research has shown a large increase and, consequently, journals such as '*Bioinspiration & Biomimetics*' or book series such as 'Biologically-Inspired Systems' [5, 16, 24, 29, 64] or 'Biomimetics: Nature-Based Innovation' [8] are much needed.

3.1.3. Biomorphic developments

Another important attribute is the planned transfer of organic morphology, on the one hand, and the unintended natural appearance of technical products, on the other hand. This is interesting insofar as biologically derived developments do not have a specific design language that makes its origin from biology clearly recognizable. However, 'biomorphic' shapes and patterns, e.g. in architecture, design and robotics, result from the conscious transfer of a biological model's organic morphology. Natural forms and structures (e.g. flowers, plants, curved lines) were already used by Art Nouveau artists. Well-known architectural examples are the Vienna Secession building with its dome consisting of golden laurel leaves [92] and the Crystal Palace, a cast-iron construction built by the gardener Sir Joseph Paxton being inspired by the ribbed leaves of water lilies [15]. In recent years, many designers have created lamps transferring the morphology of biological archetypes such as a tree (Werner Aisslinger, treelight from 2007), an artichoke (Poul Henningsen, PH Artichoke lamp from 1958) or a dandelion (Richard Hutton, pendant lamp Dandelion from 2004) [57].

3.1.4. Biotechnological developments

In contrast to bio-inspired, biomimetic and biomorphic solutions in which living organisms are exclusively indirectly used in terms of a concept generator, 'biotechnological products' such as synthetic insulin or synthetic penicillin are technical applications in which living systems or derivates thereof are directly used in the synthesis of products. Moreover, 'bio-based materials' belong to biotechnological developments in the broader sense, because they are produced from substances derived from (once) living organisms.

3.1.5. Technical developments with natural appearance

In this context, the 'natural appearance' of a technical product is not the stated aim in the process of development but might be the result of a sophisticated design process that also gives the product an aesthetically attractive appearance [75]. Occasionally, the natural appearance is so convincing that, subsequently, a biological archetype is read into it and the product is nicknamed. A good example is the Beijing National Stadium in China, also known as the Bird's Nest because of its interwoven steel composing the visible façade. Especially in China, the bird's-nest analogy for Herzog and de Meuron's stadium is associated with positive feelings, not least because a bird's nest is an extremely expensive and rare gourmet specialty [43].

3.1.6. Technical developments in parallel to biology

A special feature is the 'technical product developed in parallel' characterized by an engineer-driven development with a special function that was in parallel evolved in biology in the course of evolution. Both, in biology and in technology, a variety of operating principles may lead to a special function. In other words, having the same function does not necessarily mean that the solutions possess the same operating principle. One interesting example of this, are the self-cleaning roof tiles Erlus Lotusan®, being spontaneously associated with the Lotus-Effect® because of the name-related trademark. In contrast to the biomimetic developments with Lotus-Effect® (see also chapter 3.1.2), the tiles have no biological role model and possess a totally different operating principle in terms of photocatalytically active concrete surfaces that destroy dirt particles [63]. If the technical and the biological solution have the same function and the same underlying operating principle, they are often lookalikes. Impressive examples for this are the suction cups [17]. The first technical sonar systems were originally developed independently of animal echolocation [40]. Nowadays, bio-sonars might serve as an inspiration for special applications of technical sonar systems.

3.2. Normative aspect: contribution to sustainability

Knowledge transfer from biology to technology takes place in a variety of precisely describable ways leading to several classes of bio-derived solutions, in general, and bio-inspired developments, in particular (see chapter 3.1). In addition, learning from living nature is linked with the desire and hope of learning from biological solutions that have been optimized over the course of 3.8 billion years of evolution. Thus, bio-inspired solutions ought to come together with the promise of exceptional quality in terms of a contribution to sustainable development by fitting into natural cycles, lower levels of risk, fault tolerance, environmental compatibility, energy and material efficiency, and many others [11, 47, 49, 50, 76–79]. Time and again, in popular and scientific literature the reader comes across with general statements about bio-inspired developments from a normative and/or emotional perspective. Here, only some selected statements should be mentioned. Benyus [11] summarize at the beginning of her book 'Innovation Inspired by Nature': '*Nature as measure. Biomimicry uses an ecological standard to judge the 'rightness' of our*

Table 1. Descriptive, normative and emotional content of bio-derived developments.

Aspect	Describes …	Bio-derived developments
Descriptive content	… the reality	– Definitions
		– Approaches
		– Classification
Normative content	… the ought	– Extraordinary quality
		– Contribution to sustainability
Emotional content	… the emotional perception	– Feelings
		– Moods
		– Hopes

innovations…'. Mazzoleni [44] writes in the introduction of her book 'Architecture follows Nature': '*Sustainable design is a way for us to begin to harmonize man-made structures with the natural environment. Biomimicry can help us change our perception by looking to nature as a source of functional and aesthetic solutions rather than as a source of obstacles to overcome*'. In summary, to rationalize and refine the discussion about bio-derived developments, descriptive, normative and emotional aspects have to be taken into consideration (table 1).

During human cultural history, the vision of sustainability has been redefined continuously in order to give orientation and to act as a guidance and motivation [26]. Despite of this long history, it is still an elusive term, questions of 'sustainability' do not have a simple 'yes/no' answer [6], and assessments of 'sustainability' cannot fall to zero. Many attempts have been made to measure sustainability and therefore numerous assessment methods are recently available, but the choice is left to the practitioner. Most frameworks suggest an assessment of the three pillars separately, enhancing the method previously well established for ecological assessment—the Life Cycle Assessment (LCA)—to all pillars [18, 32, 36, 86]. Hence, Life Cycle Sustainability Assessment is defined as a combined assessment of Life Cycle Costs, Social Life Cycle Assessment and Environmental Life Cycle Assessment. Meanwhile several methods such as 'pro Suite' [86], 'PROSA' [25, 87] and 'Calcas' [88] have been developed including these aspects. In the context of sustainable products inspired by biology, the method of sustainability assessment is not specified. Rather, it is of upmost interest to clarify whether the contribution to sustainability stands on its own or only applies in relation to a (conventional) reference system. In case of using a comparative approach, the sustainability assessment striven for ought to be identical.

Recently, the term 'sustainable development' is preferred, because it refers to growth and progress. Nevertheless, 'sustainability' and 'sustainable development' formulate an anthropocentric target state of inter- and intra-generational equity by accomplishing environmental (or ecological), economic and social aims. Bearing in mind that, in living nature, both anthropocentric perspective and teleological thinking and acting are unknown [3, 58], we need to clarify in what sense natural concept generators can serve as templates for sustainable developments. Particularly interesting in the nature versus culture context is the question as to whether the exceptional quality of 'bio-derived solutions' is an implicit and/or explicit contribution. The implicit contribution by means of a by-catch through various types of knowledge transfer from biological models to biomimetic developments was coined by von Gleich as 'biomimetic promise' [76–79]. This questionable effect might be intensified by a conscious transfer of knowledge in the context of environmental, economic and social sustainability. In the framework of BID the generation of sustainable design is explicitly envisaged [22, 47]. In the context of ecosystem biomimicry the potential of sustainable building engineering are explicitly addressed [11, 49, 50].

O'Rourke and Seepersad [47] focus on sustainability by means of energy- and materials-efficient designs using biological analogies during ideation. Apart from the fact, that the terms 'efficiency' and 'analogy' mean different things to the researchers (see also [27]), they found further obstacles why not all BIDs are efficient. Even if an efficient-related role model was chosen, the BID is not efficient because, first, it is too difficult to abstract the traits from biology and incorporate them into technical design, second, the environments and constraints of biological and technical systems are too different, and third, over the product's life cycle the efficiency advantage may be countered by unintended effects. Raibeck *et al* [46] could illustrate this effect within a life cycle inventory study on lotus-inspired self-cleaning surfaces. Comparing the environmental performance of bio-inspired surfaces with standard industrial cleaning techniques shows apparent benefits during use phase, but production burdens can outweigh them.

Coming back to the attributes and values of the dataset and the provided decision tree (supplementary appendices 1, 2, figure 2), it is noticeable that at first glance sustainability-related attributes or values do not show up. A reason could be that this is the consequence of a so-called 'change of categories'. Having a closer look on the environmental impact categories being measured within a sustainability assessment, we find for instance 'global warming potential'

(greenhouse gas emission like CO_2, see also chapter 2), 'primary energy demand' (total energy input of all renewable and not demand renewable forms of energy), and 'land use' (amount of land needed to fulfil the function of an investigated product system). These sustainability-related categories can be addressed by the transfer of efficiency-related knowledge transfer (operating principle, morphology, and application of biomimetic algorithms) from biology to technology. A well-known example is the Mercedes-Benz bionic car inspired by several features of the yellow boxfish *Ostracion cubicus* [47, 89]. Transferring the boxfish's ideal aerodynamic morphology (drag coefficient of the true-to-the-original model cd = 0.06) results in an outstanding aerodynamic efficiency of the concept car (drag coefficient cd = 0.19). In addition, the construction principle of angular, cube-like body with its bony armour was transferred to the car in terms of safety and comfort in order to accommodate four people and their luggage. By applying the biomimetic algorithm of Soft-Skill-Option to the entire body-in-white structure, a biomimetically optimised lightweight construction has been generated. While the weight is reduced by some 30%, the high levels of stability, crashworthiness and driving dynamics remain unchanged. As mentioned by [47] it is important to verify that all features remain efficient in the design context. This is even more astonishing because in the field of aerodynamics it is not easy to scale-up from a 45 cm long fish swimming under water to a 4.24 m long car driving in air. An empirical study carried out by O'Rourke and Seepersad [47] show that compared to conventional car shapes the Mercedes-Benz bionic car shape shows environmental impact advantage. The same refers to the biomimetically optimised frame in comparison to standard car frames. Even more informative as a point of comparison would have been a quantitative analysis. Such a quantitative comparison of biomimetic and conventional solutions from the building sector is presented in detail in chapter 4.

3.3. Emotional aspects: feelings, moods and hopes

Apart from the descriptive and normative content, our personal and emotional perceptions of biology and technology are important for our emotional attitude to technical and bio-derived applications. The fascination of natural systems and the reverence for life are transferred to bio-inspired products and thus release positive emotions. If the term biomimetics is used in combination with other words, emotions may change because of individual perception, knowledge and experience. An impressive example could be 'nanobiomimetics', which describes the development of biomimetic products at the nano level. Because, in the field of nanotechnology, very little is known about the effects of exposure to nanoparticles on humans and the environment, the general population is anxious and uneasy. These negative thoughts and feelings might then be transferred onto nanobiomimetic applications in particular and/or even onto all biomimetic products.

Even technical products with natural appearance are associated with positive or negative feelings [59]. Especially in the context of architecture, '… *biomorphism can add further meaning than would be achieved from a purely technical use of biomimicry… Architecture should always have an emotional dimension—it should touch the spirit, it should be uplifting and it should celebrate the age in which it was created*' [48]. Moreover, the shape and design of buildings can generate associations finally leading to common used nicknames. The Beijing National Stadium has been nicknamed 'Bird's Nest' [43] and the City Hall of London got the nickname 'The Armadillo' [90]. The emotional perception is usually a crucial aspect for the market potential of innovative products. A positive connotation of bio-inspired products might enable, or at least enhance, their market introduction.

A variety of sustainability assessments also measure the user's perception of a product. In the framework of 'PROSA', the symbolic utility of products can be qualitatively assessed by using a checklist of attributes with respect to, for example, external appearance, specific design, prestige, feelings, moods and hopes [25, 87].

4. Case study: 'bone-like slab'

In the context of a case study from the building sector, the findings concerning the descriptive, normative and emotional aspects of biomimetic developments with special focus on the contribution to sustainability aims will be illustrated in detail.

4.1. Descriptive aspect: classification

The biological concept generator for the ribbed slab of the old zoology lecture hall at the University of Freiburg was the morphological-anatomical structure of hollow bones and the course of bone trabeculae following the stress trajectories in the direction of the main loading condition. This knowledge transfer resulted in a slab with isostatic ribs made by reinforced concrete. Bones and the ribbed slab are lightweight constructions and '*the cancellous bones trabeculae of the femur have the function as the ribs in the lecture hall slab*' ([30], translation from [2]). With respect to the presented decision tree (figure 2), the lecture hall's ribbed slab can be classified as a 'functional biomimetic and biomorphic product'.

The ribbed slab has a diameter of 23.86 m and is mounted on a hollow reinforced concrete pillar and two curved wall supports. This specific structural condition leads to a specific geometrical arrangement of the isostatic ribs (figure 5), which guarantees the most possible stability together with the lowest possible material input [30, 31].

Figure 5. 1:20 scale model of a bone-like slab. Loading analyses with a homogenous plate of equal thickness based on photoelasticity were necessary to find the orientation of the isostatic ribs. The ribbed scale model equipped with strain gages was tested under various load scenarios.

4.2. Normative aspect: sustainability

A first qualitative sustainability assessment on the basis of the integrative sustainability concept of the Helmholtz Association [37] was carried out on the ribbed slab in comparison with a massive limp reinforced slab available back in 1968, when the lecture hall was built. Because a massive slab is definitively not a lightweight construction and additional material and reinforcement would be necessary for the three ceiling supports, a massive slab seems not to be an adequate alternative for analysis in detail. For this very reason, the biomimetic slab gains advantage because of the lower material input in the fields of emission protection, resource efficiency and reduction of environmental impact [4]. Furthermore, a quantitative comparative sustainability assessment on the basis of 'PROSA' [25, 87] was carried out. In this case, two conventional lightweight alternatives in terms of a hollow article slab and a pre-stressed flat slab available in 2010 were chosen. No fundamental differences between the three slab constructions could be found with respect to Social Life Cycle Assessment. Concerning Life Cycle Assessment, the three alternative slabs lay in the same range with the exception of the category 'land use', whereby the impacts of the ribbed slab were 52 times higher than that of the alternatives. In the field of Life Cycle Costing, the category 'overall material costs' was in the similar range, whereas the 'building costs' of the ribbed slab was 2.2 times more expensive than the other options. The differences found in the impact categories 'land use' and 'building costs' were the result of the work-intensive and time-consuming production of the wooden formwork required because of the very complex geometry and the use of wood for the formwork. The chosen land use assessment method is a solely quantitative one, not taking into consideration the way in which the land is utilised or the land use type influences land-use-related ecosystem services [10, 12, 91]. A closer look shows that the ribbed slab has a 3.6-fold and 4.4-fold higher beneficiation because of the combustion of the wooden formwork compared with the two alternatives. In summary, the 'biomimetic promise' can be said to be retained for the bone-like slab, given by a positive validation of the biomimetic check and subsequent sustainability assessment [2]. However, this result makes no assumptions about the conscious knowledge transfer of sustainability parameters from the biological role model to the technological solution. As far as we know from the literature, in the 1960s, sustainability aspects did not explicitly play a role during the planning and building phases of the ribbed slab of the lecture hall. Nowadays, sustainability aspects play a particularly significant role in the construction sector [21].

4.3. Emotional aspects: aesthetics and symbolic character

In the framework of both the integrative sustainability concept of the Helmholtz Association [37] and 'PROSA' [25, 87], the exceptional geometry of the ribbed slab can be considered as an additional architectural benefit from an aesthetic perspective (see [59]). Furthermore, that the architect consciously used the inner bone structure as a biological role model for the construction of the ceiling of the zoology lecture

hall in which biologists were trained has a strong symbolic character [2, 4].

5. Conclusions

Research and development in interdisciplinary environments markedly have increased in importance over the past few years. This also holds true for the interrelationship between natural sciences (biology) and technology (design and engineering). Interdisciplinary work also enables the meeting of different ways of thinking, methodological approaches and scientific languages with their own definitions of technical terms. Therefore, scientists are now calling for clarifying attributes and their respective values in order to unambiguously describe key terms. However, more certainty and clarity does not simply mean the invention of new terms, as some might not be self-explanatory or might, at the very least, be unclear or ambiguous. Rather, there is a need to find a system that describes, as accurately as possible, the developmental history of biology-derived and technology-derived solutions, precisely because no meaningful language presently mirrors the history of this development in terms of biological models, knowledge transfer from biology to technology and maintenance or modification of function. This also means that the classification of a technical development is not possible without knowing the developmental history of the solution in detail.

As pointed out, the development of a biomimetic product is a benefit not only for the designer and engineers, but also for the natural scientists in terms of so-called 'reverse biomimetics'. The classifier presented here is an accurate model on basis of a provided dataset with currently relevant biology-derived and technology-derived developments. This dataset can easily and anytime be supplemented by new examples and adapted in terms of additional attributes and values. Recent and future dataset-derived decision trees are straightforward tools in the sense of an identification key and can 'grow along' with the ongoing increase of nature-derived products.

The descriptive, normative and emotional content of biology-derived and technology-derived developments have been described in general on the basis of a state-of the-art literature review and, in particular, in the context of the case study of the 'bone-like slab'. With focus on the descriptive aspect of bio-derived and technology-derived developments, the user of the provided classifier needs background information about the nine descriptive attributes and their respective values to unambiguously identify the respective class. Learning from living nature promises extraordinary quality of the technical application, which is mirrored by the normative and emotional aspects. Bearing in mind that living nature is not sustainable in the sense of the human-made vision; normative statements nevertheless claim that bio-derived applications ought to be sustainable. Although 'sustainability' on an abstract level of concept or vision cannot be directly transferred to technical developments, there are characteristics relating to energy efficiency, materials efficiency, emission reduction and others that should be identified, systematically studied and integrated in the development process of innovations. With focus on bio-derived solutions this can take place by transferring operating principles, manufacturing processes, and morphological features and by creating powerful biomimetic algorithms which were applied thereafter. The fascination of living natural systems can be transferred to bio-derived products and mostly causes positive emotions. However, emotions may change because of individual perception, knowledge and experience.

Future studies should take into account a detailed documentation of the development process to provide background information for the classification, the boundary conditions of the biological model and the product context to avoid obstacles, and comprehensive sustainability analyses to identify advantages and unintended effects during life cycle that may counter the positive effect. Sustainability assessments of bio-derived developments should come along with those of conventional products, both carried out with an identical assessment methodology to allow direct comparison. These results are followed by further questions concerning a systematic generation of bio-derived applications contributing to sustainability. Some key questions are:

- Which biological role models are suitable, if one considers that living nature itself is not sustainable in the sense of the vision 'sustainable development'?
- Which sustainability-related characteristics are essential, if a systematic knowledge transfer of sustainability aspects from biology to technology is envisaged?
- What role does multifunctionality of biological models play for single-objective and multi-objective optimisation of bio-derived applications (e.g. Pareto Optimum), not least with respect to sustainability?
- How will bio-derived solutions influence sustainable products, buildings and cities?

These questions and further challenges that arise from them will be addressed in the framework of CRC-Transregio 141 'Biological Design and Integrative Structures—Analysis, Simulation and Implementation in Architecture'.

Acknowledgments

This project is funded by the German Research Foundation in the framework of the CRC-Transregio 141 'Biological Design and Integrative Structures—Analysis, Simulation and Implementation in Architecture'. This work is also supported by the Ministry of Science, Research and the Arts of Baden-Württemberg in the framework of Sustainability Center Freiburg. We are particularly grateful to Thomas Speck for stimulating and critical discussions. We like to thank Hans-Dieter Hecker (Freiburg, Germany) for providing us with first-hand background information and the 1:20-model of the ribbed slab at the University of Freiburg.

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