APPLICATION OF BASIC DESIGN PRINCIPLES FOR SOLUTION SEARCH IN BIOMIMETICS

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ABSTRACT
The main purpose of biomimetics represents the solving of technical problems by searching solutions in biology and transferring these into engineering. This approach leads to a high degree of innovation that is often needed in product design. The process of finding adequate solutions in biomimetics is very challenging. Problems lie in the difficult communication between engineers and biologists due to differences in terminology and design methods. In this paper a method of improving the solution search process in biomimetics by using basic design principles is presented. From existing design principles in biology and engineering, biomimetic principles are derived. With the aid of biomimetic design principles engineers and biologists can conduct the search for solutions faster and more effective. The biomimetic principles are embedded in an application process. Hence, the user is conducted systematically and is offered a range of possible solutions for the stated problem.

Keywords: product design methods, biomimetics, solution search, design principles, innovation

1. INTRODUCTION

Finding solutions for design problems that are innovative and can fulfill stated requirements best is one of the main challenges that engineers face during product design. A great source of new and innovative ideas represents the surrounding nature. This source of ideas is used within biomimetics where results from biology are used to resolve technical problems.

In biomimetics several tools and methods exist to sustain the solution search process. Construction catalogues and association lists are only some few examples. These tools use mainly functions and geometrical and qualitative criteria to structure biological solutions and their application is very complex. Tool users often must be experts in biology and engineering to achieve valid and effective results. The development of a biomimetic product is realized mostly within an interdisciplinary team. Major differences in terminology and design models and the resulting difficult communication and knowledge transfer are hereby further problems. The transfer process of a biological solution into a technical product is also extremely problematic and is not realized systematically. Therefore, an intuitive solution search process is required at this stage. The method planned has to exhibit a higher degree of abstraction so that engineer and biologists can use it from the start without further training. The research question stated is therefore: *How can the solution search in biomimetics be improved without the need of multidisciplinary (biology and engineering) knowledge?*

To resolve the illustrated problems and to enable an improved and effective search for solutions basic design principles are very useful. Basic design principles are used in engineering as well as in biology to help designers improve the products and assure that requirements and goals are met. They have a prescriptive character and serve as elementary design guidelines [1]. They are also characterized by a high degree of abstraction and can therefore be manifold applied. From the design principles in biology and engineering biomimetic principles are derived and embedded in an application process which helps the user to identify solutions. The method has to fulfill several objectives:

- Optimized solution search
- Optimized communication between engineers and biologists
- Exclusion of additional knowledge acquirement and training of biologists and engineers

2. STATE OF RESEARCH AND MOTIVATION

2.1. Biomimetics

In biomimetics two main approaches can be distinguished: bottom-up and top-down biomimetics. The top-down process describes the search for biological solutions for a stated engineering problem. This approach is the most used process in biomimetics due to the high demand of innovative ideas in engineering. The bottom-up process deals with the identification of technical application areas for biological solutions with high innovation and realization potential [2].

For the search for solutions in biomimetics several tools were generated. These tools are mainly based on catalogues which are used as data bases to identify adequate solutions in biology. The top-down and bottom-up biomimetic process can be supported by using existing solution search tools in a more or less extensive way, depending on the situation and problem to solve. The tools need also detailed know-how in biology and engineering for an effective and successful application.

The core element of this paper, the application of design principles, can be used as an effective tool for solution search. A vast range of principles can be found in engineering as well as in biology. These principles are used to develop applicable biomimetic design principles.

2.2. Solution Search Tools in Biomimetics

For solution search in biomimetics a vast range of tools and methods, which differ from each other in design, searching approach and application area, have been generated. These tools and methods contain either approaches from product development that have been adapted for the use in biomimetics or new methods and applications which are realized to help users manage the solution search process. These tools support mainly the allocation of biological solutions to engineering design problems (top-down process). Significant tools are for example the seven thinking steps by Rechenberg [3] and the biomimetic searching strategy by Zerbst [4]. The searching strategy is realized within both approaches by algorithms used to identify biological archetypes. The searching strategy by Zerbst represents an enhancement of the approach by Rechenberg by integrating the handling of models in the algorithm.

Hill [5] and Gramann [6] use functions to structure biological solutions. By using similar terminology the communication between biologists and engineers can be improved. The model described by Hill contains a biomimetic thinking- and action process which can be applied in form of a solution catalogue. Gramann generated an association list and a biomimetic application model with three main steps embedded: “Formulation of the searching goal”, “Allocation of biological systems” and “Analysis of allocated systems”.

To identify biological solutions by using analogies in nature including the assessment of similarities between biology and engineering Vakili and Shu [7] and Jordan [8] suggest analogy models. The biomimetic concept generation approach by Vakili and Shu offers users strategies to identify analogies in nature. The focus lies in generating a vast spectrum of ideas for the solution search process. The model presented by Jordan requests the definition of problem-related aspects in both disciplines and the drawing of connections between them. The model is very general and describes ways to overcome communication problems between disciplines by generating relation networks.

Other relevant tools are the guideline for biomimetic approach and design by Küppers and Tributsch [9] and the solution catalogue provided by Löffler [10]. Küppers and Tributsch combine a layer-model (layers: revelation, technical biology, technical biomimetics, imitation and application) with a “biomimetic similarity matrix”. The solution search catalogue by Löffler structures the biological solutions by using a software data base.

Finally, the most relevant solution search tool in our case represents the catalogue for biomimetic design with 10 theses for biological design by Nachtigall [11]. The catalogue contains a variety of biological phenomena structured by functions. Nachtigall postulates 10 basic design principles applied in biology. The goal of the generated principles is to make engineers sensitive regarding the functionality and design rules of biological systems.

2.3. Basic Design Principles

Basic engineering design principles represent general strategies. They can be found in many different methods and have a major influence on their mode of operation. Basic design principles are applied in many different disciplines and are orientated towards helping developers in achieving an overall improvement of their projects. They can be applied in many different situations and have an abstract

and prescriptive character. The prescriptive character defines the composition of design principles. They consist of repeating and often applied approaches and methods for solving problems. Further they can be used independent of the problem stated and have a vast application field [1].
Biological design principles describe mainly the design and functionality of biological systems [2].
Natural science disciplines which engage in generating products use basic design principles as guidelines through the development process. These principles are adapted for the specific discipline and illustrate the main problem areas tackled. Design principles can be applied over the entire product development process, from the conceptual phase up to the complete product.

2.4. Motivation

The presented biomimetic solution search tools help users only under several constraints. The tools are characterized by a very complex design, a difficult application and the need of specific know-how. Mostly they are designed as catalogues which use various criteria like functions, geometric properties and graphical representations to structure biological solutions. The tools are widely static and do not support a continuous and complete actualization of the contained information. Problematic is also the difficult communication between engineers and biologists due to the missing terminology and “translation methods”. Interdisciplinary team work is not supported by the described tools.
According to Pahl and Beitz [12] a general working methodology should fulfill following objectives:

- Widely applicability
- Discipline independence
- No requirement of specific know-how from the user
- Structured and effective thinking process support

By using basic design principles for identifying solutions in biology and transferring these in engineering three of four stated goals can be completely fulfilled. Due to the high degree of abstraction displayed basic design principles are widely applicable and require no further specific know-how. Engineers and biologists can communicate with each other on an abstract level without the need of further terminology. Also design principles support a structured and effective thinking process. Only the goal of being discipline-independent cannot be entirely fulfilled. Some of the existing basic design principles achieve this goal, for e. g. the basic principle of efficiency or transparency, but there are also many principles which can only be applied in specific situations.

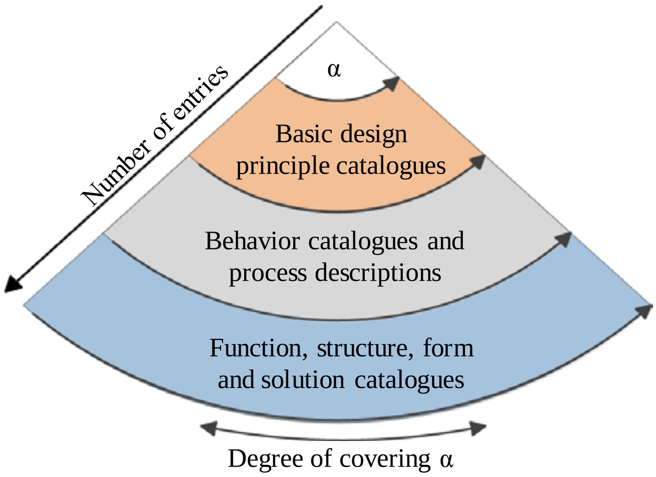

Figure 1. General catalogue types [5], [15]

Figure 1 displays the degree of solution space coverage over the number of solutions contained of three main forms of structuring methods. The methods are used for designing solution catalogues. They are grouped under three main topics. The first topic contains solutions structured by function, structure and form, the second topic solutions structured by behavior and process and the last topic contains the use of basic design principles for solution identification. The first two topics show a higher number of recorded solutions but the same degree of coverage of the analyzed solution field compared to the use of basic design principles. With the aid of basic design principles users can invest less time and effort in searching for solutions in biology to achieve their goals. However, no

assumption can be made regarding the final number of solutions identified by applying each of the structuring methods.
To simplify the solution search process in biomimetics and overcome the stated problems we developed biomimetic design principles which can be used without further training by engineering and biologists likewise. The method supports the top-down and the bottom-up process in biomimetics. This fact has been tested in two representative use cases.

3. REALIZATION AND RESULTS

The design of the solution search method by using basic design principles follows six main steps:

1. Problem and situation analysis
2. Requirement collection
3. Collection of biological and technical basic design principles
4. Generation of biomimetic principles
5. Embedding of biomimetic principles in an application process
6. Top-down and a bottom-up method application

The first step consists in analyzing and structuring of the tools used for solution search in biomimetics. From the gathered information, requirements are collected. Examples for important requirements are a user-friendly tool application, the support of interdisciplinary team work and the independence from model actualization and completion. Next the collection of basic design principles from engineering and biology is realized. From the collected principles, relevant principles are extracted and synthesized into biomimetic design principles. To be able to apply the generated principles by engineers and biologists equally a suitable application process is needed at this stage. Through the integration of the biomimetic principles into an application process the solution search can be conducted systematically. As a last step the method is applied in two representative use cases. The use cases reflect the two main biomimetic approaches: top-down and bottom-up biomimetics. The results generated from the use cases are used for the improvement of the model. The comparison of achieved results with the stated requirements at the beginning of the process is also very important and was performed continuously through the entire development process of the model.

3.1. Biomimetic Principle Generation

To support the interdisciplinary process of solution search in biomimetics, specific biomimetic basic design principles are generated. Biomimetic design principles are needed as a communication path between engineers and biologists. Engineers can use design principles from biology to search for solutions and biologists technical design principles to identify relevant application areas for biological solutions in engineering. This approach can be realized only in a limited range and runs widely unorganized and without methodical support. The identified solutions are not validated and verified regarding applicability and transfer potential. By generating biomimetic principles it is assured that the principles are adjusted in an optimum way to the problems stated in biomimetics and reflect the issues tackled within. Also, by applying biomimetic principles the identified solutions have a high potential of being more suitable for biomimetic transfer.
The generation of biomimetic design principles occurs by collecting basic design principles from biology and engineering. The collected design principles are matched and searched for analogies and similarities. The analogies are then structured and combined into biomimetic design principles.
The biological design principles identified in literature differ very much regarding content, goals and application areas. Therefore the biological principles are restructured and recombined. Altogether nine different literature sources were used for the realization of the biological design principle collection. The biological design principles are comparable to the characteristics and properties of living organisms. These are [13], [14]:

- Material and energy exchange
- Growth, development and differentiation
- Sensory performance, excitability and communication
- Genetic continuity and heredity
- Interaction with the environment
- Reproduction
- Evolution

The engineering design principles are extracted from six different literature sources. Many engineering design principles are related to the terms “sustainability” and “user-friendliness”. These two principles are very important regarding our efforts in building a bridge between biology and engineering. Table 1 displays the collected and structured design principles from engineering and biology. On both sides twelve major design principles are identified. Every design principle is used in the discipline in case for system optimization and problem solving and represents a main design topic.

Table 1. Technical and biological design principles

Technical design principles	Biological design principles
1. Principle of user-friendliness	1. Principle of cycles
2. Principle of division and combination	2. Principle of adaptivity
3. Principle of transparency	3. Principle of network system design
4. Principle of application of standards and norms	4. Principle of modularity
5. Principle of economy	5. Principle of forced efficiency
6. Principle of self-help by physical laws	6. Principle of multi-functionality
7. Principle of safety	7. Principle of reproduction
8. Principle of observation of the whole	8. Principle of predetermined time periods
9. Principle of planning	9. Principle of dynamics and flexibility
10. Principle of artificial time periods	10. Principle of communication/networking
11. Principle of community use	11. Principle of learning
12. Principle of methodic approach	12. Principle of resilience

Between the displayed design principles of the two disciplines technology and biology (“T” and “B” in Figure 2) various correlations and dependencies can be depicted. Every combination of design principles is analyzed and the correlations found are registered with the help of a matrix. The depicted analogies can be summarized to superior topics. These topics represent the biomimetic design principles. Interesting for a potential transfer into biomimetic principles are those principles which display a minimal consistency. This is very important because biomimetic design principles represent a discussion base for engineers and biologists in equal measure.

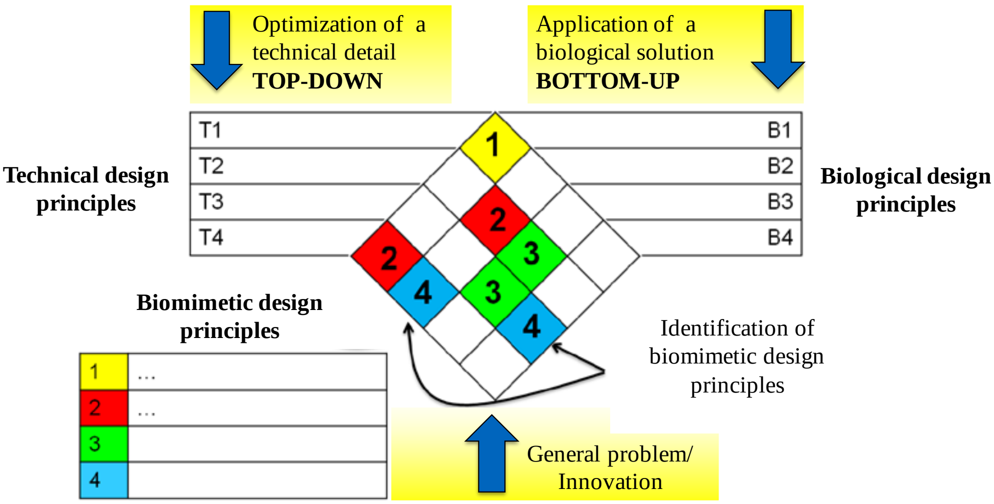

Figure 2. Design principle matrix (simplified)

The seven generated biomimetic design principles are displayed in Table 2.

Table 2. Biomimetic design principles

Biomimetic design principles
1. Principle of efficiency
2. Principle of duplication

3. Principle of modularity
4. Principle of observation of the whole
5. Principle of disturbance minimization and elimination
6. Principle of environment and community compatibility
7. Principle of combination

3.2. Basic Design Principle Application Model

The engineers and biologists which use the generated biomimetic design principles for solution search must be supported in their actions by guidelines. The handling of the biomimetic design principles can be improved by integration into an application process. The application model gives precise information regarding how to use the identified and the generated design principles.

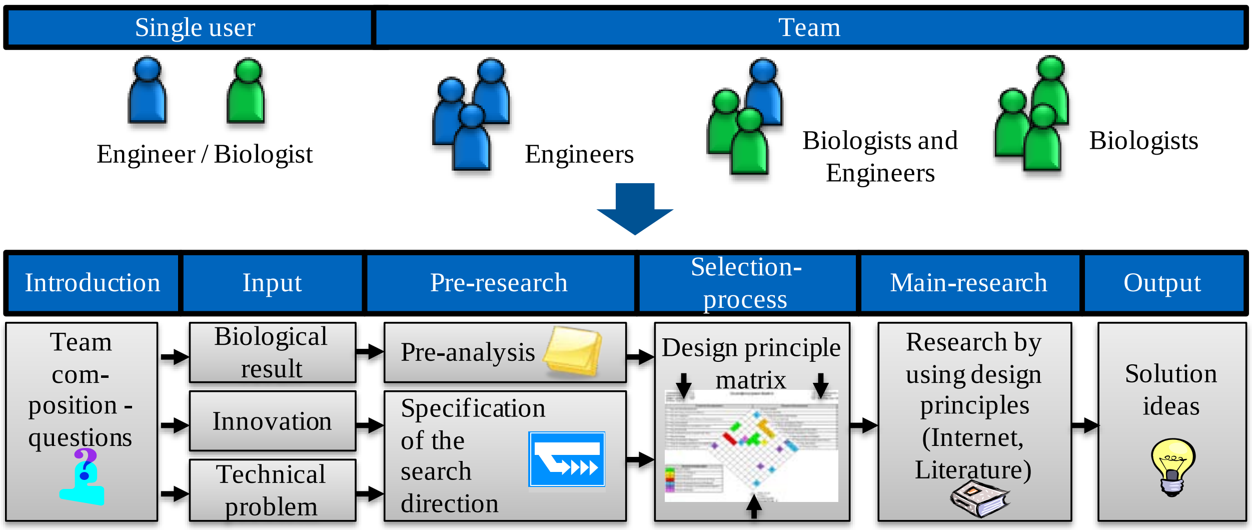

Figure 3. Design principle application model

Figure 3 displays the six main steps of the application model. At first the user is offered sensitization questions regarding the composition of the team. Next the input of the application model has to be established by the user. Three input-types are offered hereby: biological results (bottom-up), innovation and the technical problem (top-down). These three input-types can be analyzed in the pre-research part of the model by realizing a pre-analysis and by establishing the search direction. With this information at hand the user can now apply the basic design principle matrix (Figure 2). After choosing design principles the user can search for solutions. Finally the user receives a set of solution ideas which he can use on solving the stated problem. The application model can be used by different user types. The user can be a single-user or part of a team. Teams can be composed by engineers and biologists (interdisciplinary team) or only of engineers or biologists (intradisciplinary team).

Figure 4 shows the number of paths that the user can pursue through the model. If the user wants to realize a top-down process and therefore to find solutions for an already stated technical problem he has to start with the technical design principles, go over the principle matrix by using the generated biomimetic principles and finally he receives a set of biological design principles with which he can go into the main research phase. Wants the user to identify application areas for valuable biological solutions and pursue therefore a bottom-up process he has to start with the biological design principles. The further approach is the same as for the top-down process only that in the end technical design principles result for searching. The last path contains the search for innovations in biomimetics. Hereby the user has a general problem to solve that is related to a high need for innovative and new ideas. He starts with the biomimetic design principles and gets technical and biological design principles as a result to start the main research.

The biomimetic design principles act as a translator between the engineering and biology design principles. The ways to use the design principle matrix are highly dependent of the problem the user has to solve.

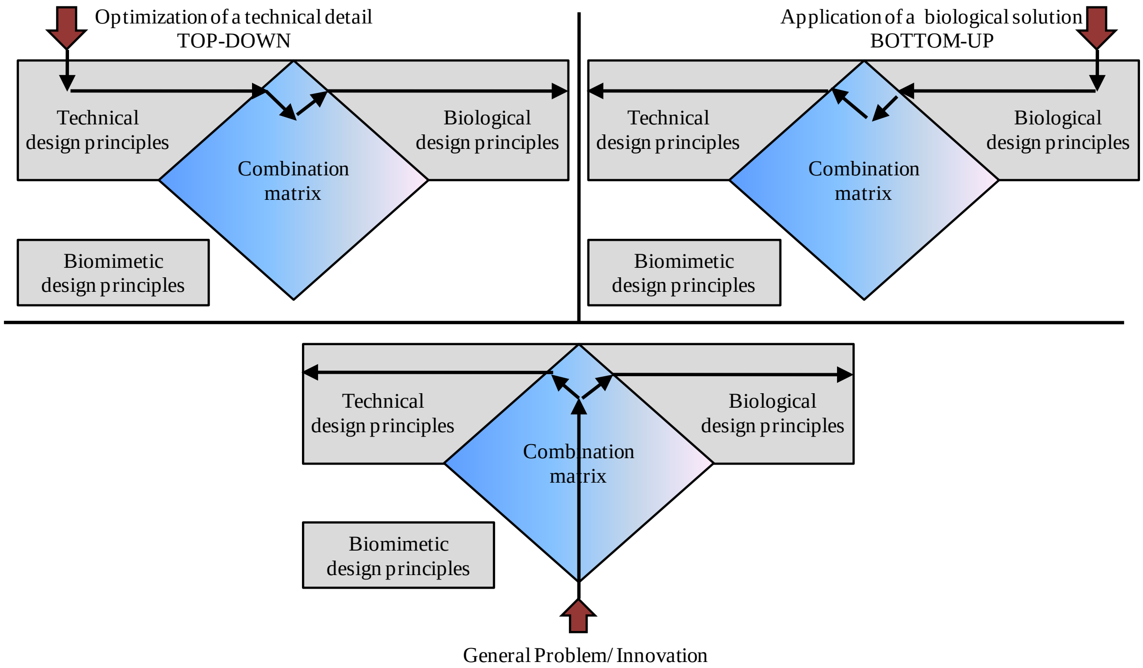

Figure 4. Application paths within the design principle matrix

4. MODEL APPLICATION EXAMPLE

The developed biomimetic design principles and the corresponding application model can be applied to solve problems bottom-up as well as top-down. The model has been tested on both processes. In this paper, only an example for the top-down process is presented. The reason of choosing the top-down use case lies in the considerably higher degree of top-down applications in biomimetics.

The use case deals with the development of indoor lamp concepts which do not blind the observer. These lamps are used to illuminate photos in an art gallery. The newest LED-technology can be used to solve the problem because of its favorable properties of consuming little energy and not producing much heat. By using common LED-lights the photos cannot be highlighted optimal because of the shadow stripes produced which divert the viewer's attention. Also the lamp design is very eye-catching and can distract the viewer in contemplating the pictures. Because of the several problems related to this solution other ideas are needed. We have here a precise technical problem for which solutions from biology can be used to find new and innovative ideas.

At first the main terms that describe the problem and the system to be improved have to be worded. With the aid of the defined terms the depiction of design principles can now be started. After selecting a range of three technical principles (principles 1, 2 and 6) biomimetic design principles can be selected by using the design principle matrix. The selected biomimetic design principles are 2, 3 and 7. As a further step the biological design principles 4, 5, 6 and 7 can be identified. The selected principles are displayed in Table 3.

Table 3. Selected technical, biomimetic and biological design principles

Technical design principles	1. Principle of user-friendliness
	2. Principle of division and combination
	6. Principle of self-help by physical laws
Biomimetic design principles	2. Principle of duplication
	3. Principle of modularity
	7. Principle of combination
Biological design principles	4. Principle of modularity
	6. Principle of multi-functionality
	7. Principle of reproduction

The main research phase can be now conducted with the gained information. This phase consists of mapping the biological solutions and a technical analysis of identified design principles.
Two promising solutions resulted from the application of the biomimetic design principles: the characteristic of a plant named „fenestraria auranthica“ to bundle light by transparent cells on the end of the leaves and the design of the insect eye. The first result was analyzed and could not be transferred into a valuable technical solution for the stated problem. The inversion of the light bundling principle to a light emitter resulted in a high light spreading effect. This is an undesired effect that cannot be used to solve the problem of focused object illumination.
The second promising result found is the modular insect eye design. Insect compound eyes have a very complex design. The transfer of the biological result into a technical solution can be realized by reducing the lamp length and integrating mechanisms for adjustment. By using calculated lamp dimensions the light can be bundled optimal. The adjustment of the light cone is one of the main design requirements. The design of the lamp is realized regarding the biological principles modularity and reproduction, principles inspired by the modularity of the insect eye. As a result several light sources which can provide the same light performance as the original light source but with smaller dimensions are generated. The new design of the lamp is achieved by scaling and further multiplication of the light elements of the lamp body. A possible design of the lamp is displayed in Figure 5.

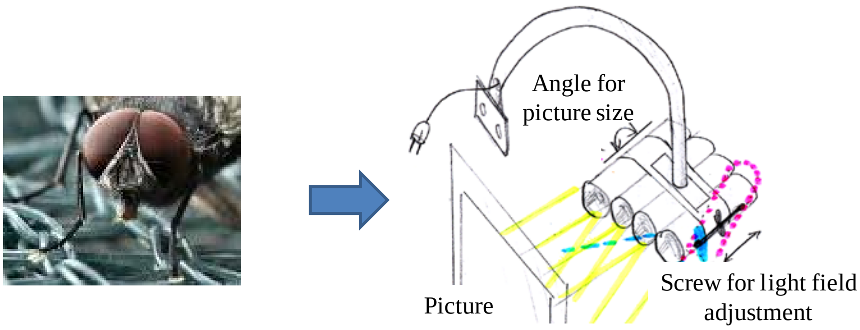

Figure 5. Lamp construction example

The lenses on the inner side of the lamp can be moved by an adjusting screw. Hence, the illuminated area can be widened or narrowed as required. Further a ball joint is designed for the precise positioning of the light cone on the picture to be illuminated.
The research took seven hours. By using the design principle matrix and the guidelines for the main research the latest research results from biology could be integrated and therefore up-to-date solutions identified. The provided example shows that the process of finding analogies from nature is very time consuming and difficult and requires intensive work and many resources.

5. DISCUSSION

The generated concept based on biomimetic design principles serves mainly for the search for solution ideas and the encouragement and facilitation of interdisciplinary work. Approaches for the systematic transfer of found solution ideas into technical products are not part of the concept and are supported only by recommendations regarding possible transfer methods and applications. The concept is designed in paper form and can be used in combination with an internet platform, a software data base or other helpful software tools. Instructions regarding when to use specific software tools or the internet are embedded in the concept.
The biomimetic design principle model reflects several advantages and disadvantages regarding design, content, approaches and set goals. Table 4 displays the main advantages and disadvantages of the model.

Table 4. Advantages and disadvantages of the design principle model

Advantages	Disadvantages
Consideration of different tasks	No full integration into the development process
Independence of solution catalogues	Some solutions cannot be structured

Advisory principle and application guidelines	Dependence of the users motivation
No research for details required	Handling of boundary conditions
Consideration of interdisciplinary team work	Dependence of the user in case
Avoidance of solution fixation	Higher work effort required

The model is designed to fulfill tasks in top-down and bottom-up biomimetics likewise. This is very important because now engineers and biologists can use the designed model equally for solving problems. In addition a third process was integrated, the identification of innovative ideas. This can also be used by both teams in equal way. The disadvantage hereby is not offering a model that supports the user during the entire development process but only in the phase of solution identification. The technical transfer is not part of the model designed and is not supported.

Another important characteristic of the model is the independence of solution catalogues and lists.

Because of the high diversity observed in nature solution catalogues and lists can never be complete. Furthermore they are not continuously updated and maintained. This problem can be avoided by using the design principle model. Hereby users can search after solutions independent of solution catalogues. Further enhancements or updates of the principle model are not necessarily required. Because of the high degree of abstraction used the terminology of the basic design principles allows to structure and organize a high amount of data. The basic design principle collection can be enhanced by other design principles or the association matrix can be completed by further principle correlations. The user can now choose from a greater range of principles and has also the possibility to compare the problem in case with the chosen principle in more detail.

The model is designed according to the adviser principle and requires a strict following of specific tasks. The embedded action guidelines represent recommendations and their application is dependent on the user's motivation.

An explicit detail research of a biological phenomena or a technical system is not required. A disadvantage hereby is the handling of boundary conditions. For the transfer of solution ideas within biomimetics the verification of boundary conditions is very important. Boundary conditions have not been integrated in the development of the model but will have to be analyzed and embedded in the future for a better model application.

The model supports interdisciplinary team work. Through the understanding of the similarities and analogies between the two disciplines the interdisciplinary team work is simplified and enhanced. The obtained optimization is although highly dependent on the user's motivation.

To avoid possible solution fixations and therefore to avoid constraining the process of identifying new and innovative solutions a research in technical areas is not planned at this stage. The consequence hereby is a higher amount of time and work to be invested.

6. CONCLUSIONS

Biomimetics has a great potential for finding innovative solutions for technical problems and represents a helpful tool for every engineer or biologist who engages in transferring ideas from biology into engineering and vice versa. This paper displays a method to enhance the solution search process in biomimetics by using specific generated biomimetic design principles. The model is developed according to a range of various requirements set at the beginning of the project. The requirements emerged out of the analyzed biomimetic solution search tools and the two use cases regarded. The focus of the model lies in the support of interdisciplinary team work and the dissociation from static and incomplete solution catalogues, which represent the actual research status. With the aid of biomimetic basic design principles from biology and engineering can be translated into each other and hence an interdisciplinary discussion base generated. To optimize the team work in engineering and biology the generated biomimetic design principles are embedded into an application process where several guidelines are supplied. The effectiveness of the model is tested within two distinctive approaches from top-down and bottom-up biomimetics.

In the future the enhancement of the model regarding further design principles from biology, engineering and biomimetics is expected. Also the identification of further analogies and associations between design principles from biology and engineering represents a very important step in optimizing the model. Furthermore the analysis of fundamental boundary conditions and the generation of integration methods for the boundary conditions into the model is a goal that has to be achieved.

The goals stated at the beginning of model development have been all fulfilled. With the aid of the principle model an optimized search for solutions can be realized in biomimetics without any use of catalogues or further searching tools. The communication between engineers and biologists could be enhanced considerably due to the translation character of the designed biomimetic principles and the matrix used. Finally users do not need any specific know-how in applying the model.

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