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Towards a theoretical clarification of biomimetics using conceptual tools from engineering design

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Abstract

Many successful examples of biomimetic products are available, and most research efforts in this emerging field are directed towards the development of specific applications. The theoretical and conceptual underpinnings of the knowledge transfer between biologists, engineers and architects are, however, poorly investigated. The present article addresses this gap. We use a ‘technomorphic’ approach, i.e. the application of conceptual tools derived from engineering design, to better understand the processes operating during a typical biomimetic research project. This helps to elucidate the formal connections between functions, working principles and constructions (in a broad sense)—because the ‘form-function-relationship’ is a recurring issue in biology and engineering. The presented schema also serves as a conceptual framework that can be implemented for future biomimetic projects. The concepts of ‘function’ and ‘working principle’ are identified as the core elements in the biomimetic knowledge transfer towards applications. This schema not only facilitates the development of a common language in the emerging science of biomimetics, but also promotes the interdisciplinary dialogue among its subdisciplines.

Introduction

Literature on the theoretical underpinnings of biomimetics is sparse because most research in this field is focused on practical applications. Biomimeticists and philosophers of science have apparently yet to discover and explore the terra incognita of the theoretical foundations of biomimetics—theoretical is meant here in a broad sense as that which complements empirical and practical work. There have, however, been some attempts at posing more conceptual questions (e.g. Vogel 2000) as well as developing a theoretical basis of biomimetics (Vincent et al 2006, Speck and Speck 2008, Nachtigall 2010, Kruiper et al 2016, Fayemi et al 2017, Speck et al 2017). In 2012, a team of biomimeticists published a guideline for biomimetics from the Association of German Engineers ‘VDI’, where a definition for biomimetics is provided. That guideline also defines certain terms and illustrates some methods. The definition is as follows: ‘biomimetics combine[s] 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’ (VDI 6220 2012:9). The draft of the German Institute for Standardisation ‘DIN’ on biomimetics (DIN ISO 18458 2015) includes a similar definition. The definition contains three important elements: (1) the abstraction from a biological model, (2) the transfer of knowledge from biology to engineering, and finally (3) the application resulting in an end product. The abstraction part actually involves what is always termed a ‘principle’. Nonetheless, it remains unclear from the VDI guideline what the term ‘principle’ actually means. The question remains: What exactly is it that is transferred from one discipline to another?

In this paper, we analyse the typical working processes involved in a biomimetic project to answer the above-mentioned question. Our approach involves adopting conceptual tools from engineering design, which represents a well-established discipline with an extensive body of knowledge pertaining to conceptualisation of designing and production (Pahl et al 2007, Colani et al 2011). Even though engineering design has been mainly developed for mechanical engineering, the framework can also be used for other branches
such as civil engineering. As shown here, these concepts and methods can furthermore be used in the field of technical biology and biomimetics. The approach can be called ‘technomorphic’ (see Maier and Zoglauer 1994) because the body of knowledge from engineering is used to understand procedures in biological research and biomimetic applications. The approach presented here also provides a clearer view not only on transferred principles, but also with respect to form-function-relationships in biology and engineering. It does not, however, provide a method to easily arrive at biomimetic products.

We start with a standard example from engineering design to illustrate the main features of the engineering design schema, and then use the schema for the standard biomimetic example, the hook-and-loop fastener. Subsequently, the Flectofan® shadowing system (Lienhard et al 2011) is investigated in more detail, together with notes on other examples, to show that the schema is applicable to most biomimetic research projects.

The engineering design framework

Engineers are typically challenged by a task which they attempt to solve by some manner of construction. In a typical textbook case, the workflow leads from the abstract level to ever more tangible solutions. Accordingly, this work flow encompasses the successive levels of: (1) task, (2) function, (3) working principle, (4) construction, and finally (5) the overarching system. This is best illustrated by a canonical example in which a component should be constructed between a motor and a mill (figure 1). The ‘task’ would thus be the ‘milling’ of cereals. In order to fulfill this task, a ‘function’ that could be termed ‘to clutch torque’ is necessary. (The phrase ‘to clutch torque’ may sound awkward, but that is how it is used in the formalised engineering design language; Pahl et al 2007.) Two shafts, one derived from the motor and the other from the mill, have to be either connected or disconnected in order to transfer torque or not. Both task and function are verbal descriptions which can be diagrammatically formalised. The term function has a specific meaning in mechanical engineering: ‘for the purpose of describing and solving design problems, it is useful to apply the term function to the intended input/output relationship of a system whose purpose is to perform a task’ (Pahl et al 2007:31). Thus the ‘task’ is that what should ultimately be achieved, and the ‘function’ is there to achieve it. Note that a function in this sense is neutral with respect to potential design solutions. It is an abstract description of what the solution should be good for. Such a function is usually displayed as a combination of a verb and a noun (Pahl et al 2007:31, Kornwachs 2015:88). Function in this sense is not a category of physics, in fact it plays no role in physics at all. Statements in physics are on a different level than the function statements in biology or engineering (see Krohs 2005:308). Physical effects are present in the schema on the next ‘lower’, the working principle level (figure 1), which can be interpreted as a description of basic cause-effect relationships in engineered systems—and later on also in biological systems, where biological effects can be included as well. The working principle contributes to fulfilling a function, but is distinct from a function.

What is the next step in the work flow for an engineer? Different ‘working principles’ have to be considered and checked whether or not they can help fulfill the function. In the case mentioned here, frictional force (F_R) produced by some normal force (F_N) is used as a physical effect to be implemented. This is the working principle chosen among other possibilities (see below). On the next, more concrete level of ‘construction’, the chosen working principle can be implemented in different ways. In the example in figure 1, the friction force is transmitted via a disc that can be brought into contact with parts that are connected both to the motor shaft and to the mill shaft. At this level, the clutch design is completed, including all constructional details and all the necessary parts to make it perform effectively.

The ‘overarching system’ (i.e. the ‘environment’ of the clutch) is, in this case, a motor and a mill. Some boundary conditions for clutch construction are determined by this larger system, e.g. the size of the shaft and the maximum allowed torque. The work flow sequence in engineering, however, usually leads from the task towards the construction. In such cases, more or less of the overarching systems are given, depending on whether only the clutch is constructed or the complete overarching system as well.

Broadly, the task can be thought of as the answer to the question ‘what for?’, the function as the answer to the question ‘what has to be done?’, and the working principle as the answer to the question ‘how?’ it is done.

On each level shown in figure 1, the engineer can choose among different ways of implementing the next ‘higher’ level (figure 2). In the above example, the working principle is a frictional force produced by a normal force. One could, however, also use a positive (form-fitting) connection to interlock the two shafts, or one could use liquids for transmitting forces. Also, towards the next level of construction, different ways of implementation are possible. Friction can be transmitted via a disk or via a cone. Hence many different constructions are possible. A clutch can also be used for different overarching systems, e.g. in a car; it can be used wherever torque should be regulated.

Note, however, that there is no unique way of how to derive the function merely from knowing the working principle alone (e.g. in the process of reverse engineering) because one working principle can also be used for different functions. For example, friction can be used in a clutch, but it can also be used when riding a bicycle, where friction between the wheel and the street is necessary. Hence, one cannot infer the function solely from knowing a working principle.
Engineering design for analysing biological systems

The conventional way of engineering is quite successful. There are, however, many yet unknown ‘engineering solutions’ that living nature potentially provides. Biological systems, their constructions, forms, and manufacturing processes perform quite well, at least most of the time. This makes considering biological constructions for engineering applications useful. Compared to engineering, in biology the work flow typically operates in the opposite direction, i.e. from the constructional solution to the problem that was solved. The starting point is almost always an overarching system that has to be investigated; and from that starting point, the ‘higher’ levels in the schema of figure 1 are inferred.

Often, the task and the function of a biological system are obvious. For example, in bird wings the task is ‘flying’ and the function is ‘to generate lift’. This is, however, not always the case. Whereas many morphological structures or shapes within organisms are well known, their functions are often not that clear, e.g. the function of the particular shape of the chin in humans, which puzzles anthropologists because it differs from the unpronounced shape in other primates for no obvious reason (see Pampush and Daegling 2016). This could be referred to by the 42-problem (after Douglas Adams’ The Hitchhiker’s Guide to the Galaxy; Vincent 2014:275): The solution is known, but what was the initial ‘question’? What are the task and the function of a particular biological construction?

To illustrate how conceptual tools from engineering design—as illustrated in the previous section—can help to investigate biological systems, we use the example of a bur (figure 3) which served as the model for Velcro® attachment products (de Mestral 1955, Velcro BVBA 2017). In this case, the overarching sys-
tem was known at the onset of research, namely a plant seed interacting with the fur of an animal (e.g., a dog). The task, i.e., ‘seed dispersal’, was also clear from direct observations. Little more, however, was known at the beginning of the investigation of this historical example, which we cite here because all the slots on the different levels in the engineering design schema were eventually filled (figure 3, third column), and an application could be made (figure 3, fourth column).

The details of the small ‘hooks’ and their interaction with fur were easy to visualize by optical magnification or scanning electron microscopy. From that
it was possible to infer the working principle. Note that there can be more than one working principle present to fulfil a single function, which in this case is represented by the combination of an elastic bending behaviour and a tight (form-fitting), positive connection. From this research result, the function could be specified as: ‘to attach object reversibly’. The display format of the function is again a verbal description, including verb and noun. Interestingly, the working principle in the application is turned around with respect to the involved structures, i.e. in the biological model, the ‘hook’ is stiff, while in the application the ‘hook’ is elastic and bends over when detaching.

Relevance for biomimetics

It now remains to be determined which of the above-mentioned levels (figures 1 and 3) is involved in the biomimetic knowledge transfer from a biological model to an engineering application. In fact, both the function and the working principle are transferred. The overarching system and the construction in the biological model show many features that are typically not transferred. For instance, the material or the particular shape of the bur (see construction level in figure 3) are not used in Velcro®. Rather, they are abstracted. The two levels of function and working principle, however, must be known in order to proceed towards a biomimetic product, and they are the same in both cases of figure 3. The task may be transferred as well, but this is not mandatory, which thus leads to two types of biomimetic transfer: (1) applications that have the same tasks as the biological model, and (2) applications with different tasks than the model. In other words: In biomimetics it is possible to divert something from its biological use or task (in German zweckentfremden), but not from its function. The following examples illustrate both these types of biomimetic transfer.

(1) A paradigmatic example for biomimetics is the aeroplane. In the construction of an aeroplane, based on bird wings, the task in the biological model and in the application is the same, namely ‘flying’. The function of the wing is ‘to generate lift’ and the working principle relates to aerodynamic effects on the wing (the same function could, however, also be created by using another working principle, e.g. via hot air in a balloon, which would not be biomimetic).

(2) In the case of Velcro®, both the function and the working principle are transferred, but not the task (see figure 3). The task of Velcro® on shoes or jackets is definitely not ‘seed dispersal’, so in this example a biomimetic knowledge transfer occurs that excludes the task. Another example is the ‘wing’ or spoiler of a sports car. This wing is not used for flying, but still generates lift, even though the lift force points in the opposite direction compared to that of an aeroplane, thereby increasing wheel grip.

Typically, in a biomimetic research project, the layers in the middle, i.e. from function to construction (see figures 1 and 3), are the subjects that need to be investigated. Research might profit from knowing the task of a certain system, but this is not a necessary precondition.

The function level

The previous sections dealt with single functions. A particular function, however, is never isolated—neither in an organism, nor in a machine or a building (see figures 4 and 5). In such entities, different functions are always interrelated. This entails a functional interrelationship in which the single functions appear as elements within an ordered arrangement (see Pahl et al 2007:41).
An organism integrates numerous important functions. The functions of an organism considered to be most central ever since antiquity are to sustain the organization (or: to guarantee its survival) and to facilitate reproduction (Toepfer 2011 vol 1, p 648). For our purposes we again use the format of the combination of a verb and a noun to describe functions, namely ‘to sustain organization’. This can be considered to be more central, with reproduction ensuring sustained organization over generations. In figure 4, this central function is connected to several basic functions that all organisms must exhibit: to metabolise, to sense, to move (in some respect also plants move), to reproduce, to develop, and to regulate. All these functions are interrelated and integrated, but their order is not strictly hierarchical. Moreover numerous connections are not considered in the figure. In order to sense, for instance, the organism needs to metabolise. Hence, it is more appropriate to refer to a web of functions or an interwoven structural fabric (in Geman Gefüge) of functions. The organism is a functional whole, whereby the single functions serve or sustain one another. Every function is embedded within a functional web.

After the canonical examples, we present a more recent biomimetic example, namely the Flectofin® shadowing system (Lienhard et al 2011), as an illustration because the background information is more easily traceable. Figure 4 shows only a small portion of all the potential functions and their interrelationships in an organism. For instance, a sub-function of reproduction in a plant is ‘to pollinate a flower’. A sub-function of ‘to pollinate a flower’ could be ‘to expose anthers’ and what is necessary therefore in a particular plant is ‘to move a surface’, for instance the petals. This example refers to the plant Strelitzia reginae Banks ex Aiton (Strelitziaceae), the model for Flectofin®.

In architecture, a similar schematic representation of functions can be utilised for buildings. Vitruvius, the Roman architect of the first century B.C., termed the three main functions of a building firmitas, utilitas and venustas (Vitruvius 1991:1, 3, 2). This is a still valid notion that can be translated to verbs for a schema of interrelationships of functions, i.e. to maintain, to protect, and to serve aesthetics. Figure 5 shows these main functions together with a selection of sub-functions that all relate to the more general function ‘to protect humans’. Again, Flectofin® is used as an example, whereby ‘to protect from the environment’, ‘to provide shading’ and ‘to move a surface’ are the subsequent sub-functions.

In the web of functions of the building example (figure 5), the function ‘to move a surface’ shows up again, which maps to the function in the organism (see figure 4). The identification of similar functions in the biological model (i.e. the organism) and the technical application (e.g. a building or a machine) (figure 6) is crucial to facilitate a biomimetic knowledge transfer. This even holds true when the functions are nested within different sites in the interrelationship of functions in the organism and the technical artefact, respectively. There must be an equal function in the biological and in the engineered system (figures 4 and 5) to establish a biomimetic transfer, at least when the function is expressed in a general way, e.g. ‘to move surface’ instead of the more specific expression ‘to move petals’.

An interconnected web—such as for the level of functions—does not exist on the level of working principles. As noted in figure 2, a particular function can be served by different working principles which are not related to each other. Furthermore, the working principles that serve different functions in the web of functions are not uniquely related to each other. In a biomimetic product, however, a particular function is always transferred together with a particular working principle from a biological model to an application. In the Velcro® example (figure 3) the function ‘to attach
object reversibly’ combined with the working principle—which can be described as an elastic bending behaviour together with a tight, positive connection—were transferred.

The development of a biomimetic project over time

In the above, we have presented a static analysis of biomimetics focussing on the relationship of construction (form), working principle and function. A biomimetic research project, however, develops over time in a characteristic way. Typically, such a project starts with a phenomenon that was discovered in a larger biological or technical system. The bur that attaches to a dog’s fur is an example for the starting point in a biological system. If the research question stems from engineering and analogous problem solutions are searched for in biology, this is termed ‘technology pull’ (VDI 6220 2012). With technology pull, the task and perhaps also the function are given on the engineering side, i.e. one looks for analogous examples in biology where these levels have already been explored. What is then inferred is the working principle and perhaps the function for which the working principle is used. In contrast ‘biology push’ is present if a phenomenon observed in biology is found to be interesting and is subsequently transferred to an application without any preceding question for engineering (VDI 6220 2012). In this latter case, no pre-defined function in engineering has to match the biological function.

In both cases, the larger biological system, which can also involve the environment of an organism, is investigated in greater detail. The complexity of the research object is thus initially very high (figure 7); e.g. when measured as the length of a compressed description of the system’s regularities as distinct from randomness (Gell-Mann and Lloyd 2004). Although an organism comprises countless features (including aesthetic ones—in the sense of the attractive appearance of something (see OED 2017)—and those that might be relevant for sustainability questions, e.g. biodegradable materials), in biomimetics the focus is usually on only a single feature that is embodied within a portion of the whole ‘construction’. Such a procedure can be named atomistic because the biological system is broken down, at least mentally, to separated entities or features, and only these singled out ‘atoms’ are used for the transfer towards applications. This must be interpreted as a descriptive statement that does not deny the possibility that more than one feature is transferred to engineering; an example is the ‘technical plant stem’ (Milwich et al 2006) for which even features from different species were utilised. As research progresses, more and more features that are found to be irrelevant for the particular goal are left aside. Correspondingly, the complexity of the investigated item decreases and the degree of abstraction increases; abstraction here is defined as the ‘removal, in thought, of some characteristics or features or properties of an object or a system that are not relevant to the aspects of its behaviour under study’ (Psillos 2007). The specific boundary conditions (e.g. particular shapes and material properties) in the biological system are successively abstracted and the inherent functions and working principles become exposed.

Accordingly, at the pivot in figure 7, the maximum degree of abstraction (corresponding with the minimum degree of complexity) is reached. At this point, the function and the working principle are sufficiently understood to be transferred towards application. Engineers can use the extracted function and working principle to draft and build houses, machines, etc.
During this application phase, the complexity of the engineered object increases, whereby the transferred knowledge from biology is integrated as one component among others that are needed for the whole technical construction. In summary, what engineers do is to take natural laws (e.g. taken from Newton’s mechanics), principles (e.g. the biomimetic working principles together with their functions), and rules (usually empirically derived, e.g. the knowledge about how long a ball bearing remains intact under certain conditions) and put boundary conditions (e.g. material or geometrical) to them in order to reach an engineering goal (see Polanyi 1968). Especially in the case of biomimetics in buildings, aesthetic considerations are typically added after and independent from the transfer of function and working principle; this was termed the ‘hard approach’ to bio-inspired architecture, while the ‘soft approach’ also strives to transfer the elegance of the biological model to the application (Speck 2015). In the hard approach, most features of the organism that served as a model are usually ignored. Architects can, however, use the biomimetic feature and turn it to an aesthetically pleasing construction. Nonetheless, such features often fulfill functional roles that do not contribute to the overall aesthetics of a building.

With regard to knowledge transfer, graphical representations are important. For the purpose of better illustration, an example is idealized, namely that leading from the flower of the plant *Strelitzia reginae* to the Flectofin® shadowing system. From the larger biological system (the model; figure 8(a)) to the larger engineered system (the application; figure 8(e)), different images or drawings are used. They represent different types of information and serve various purposes. The images next to the larger system images in figure 8 (in the middle, left and right) represent the construction levels of figure 3 (biological side) and 1 (engineering side), respectively, even though with a different example. The schematic diagram at the top of figure 8 (depicting a stick that is connected to a surface, whereby the bending of the stick results in surface movement) represents both the function and the working principle levels. Such a schematic diagram is what engineers request from the biologists, and it is an important means of knowledge transfer. Once such a schema, in which features of the biological model are abstracted, has been drafted, two goals are reached. Firstly, in order to be able to draw it, the function and working principle must have been understood. Secondly, based on this schematic diagram, applications can be constructed. Following such a schema, a first demonstrator (e.g. a working physical model) can be built. At this construction level, certain combinations of parameter settings (e.g. specific size, geometry, material parameters) can be tested in order to determine how well they work. This knowledge can subsequently be brought back to biology, a knowledge transfer that is termed ‘reverse biomimetics’ (VDI 6220 2012). This reverse biomimetics knowledge transfer (from engineering to biology) takes place on the construction level and does not change the task, function and working principle. The fine-tuning of parameters in engineering (either during the phase of building
demonstrators and complete applications or simulations) can inform biologists about which combination of parameters works best in the artefact, and hence potentially also in the biological system. Note that the levels of function and working principle do not involve particular sets of parameters—material, geometrical or otherwise. Later along the time line, during the application phase, ever more detailed engineering images are produced. Graphical representations can be understood as a continuous chain reflecting the degrees of complexity and abstraction along the biomimetic process.

The dynamics of a biomimetic project over time also raises further theoretical and conceptual questions. After naming and identifying the different conceptual levels according to engineering design, the question arises: What is taking place along the sequence in a biomimetic project (see blue arrows in figure 8)? In particular, this question must consider the development from the overarching biological system to the schematic diagram (figure 8(c)). How is knowledge at one conceptual level inferred from the adjacent one? Forms can be seen, but not functions—this may seem trivial, but the implications are not. A whole range of potential approaches can be used to infer functions and working principles (see Duncker 1992). These include morphological investigations, behavioural studies, material surveys, simulations, and inferences based on analogies (particularly important for finding form-function-relationships in palaeontology, where actualistic analogies to still living organisms are made). Clearly, one analogy that can also be made is the analogy to knowledge about well-understood constructions in engineering. For instance, technical pumps can be compared to pumping organs in order to also enrich knowledge in biology (Bach et al 2015). Trade-offs, as suggested by Vincent (2016), may be another useful concept when comparing biological and engineered systems, at least at the levels of task and construction.

Historical examples can be very instructive with regard to inferring functions. The pneumatic school of medicine in ancient Greece and Rome (starting in the 1st century B.C.) stipulated that the function of the lung is to cool the heart (Eckart 2005:22). This might sound absurd to modern researchers, but taking into account the evidence available to ancient scholars, it becomes quite reasonable. Morphologically the lungs surround the heart. Moreover, inhaled air is usually cooler than exhaled air. From this, one might conclude a heat transport that cools the heart. Clearly, at low environmental temperatures, the lungs cool the heart. Even though one can discuss what the main function of the lung is, it is clear that humans cannot survive without oxygen. They do, however, survive longer periods of external temperatures around 37 °C, where there is no cooling by the lung. Moreover, in evolutionary terms, selection was no doubt directed towards efficient gas exchange, making cooling a side effect. Examining such examples is instructive for researchers in biomimetics. How are the inferences of functions gained and at what point can one be certain to have

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Figure 8. Graphical representations along the time line of a typical biomimetic project. The arrows between the images indicate the working process along the blue degree of abstraction curve in figure 7. (a) The image of the plant Strelitzia reginae represents the overarching system of the biological model. (b) The construction level of the biological model is represented by a drawing and a microscopic image of sections through the relevant plant parts in different magnifications. (c) The schematic diagram depicts a stick that is connected to a surface. Bending the stick (indicated by the arrows at the ends of the stick) results in a surface movement (dashed arrow on top of the schema). The diagram represents both the function and the working principle levels. (d) The construction level on the engineering side is represented by an engineering drawing, with a specific geometry which was used in finite element simulations. (e) The level of the overarching system on the engineering side is represented by a picture of the working Flectofin® shadowing system. Sources: (a) B Werner, Wikimedia Commons; (b), (d) and (e) Schleicher et al (2015) (with permission).
found the ‘correct’ or ‘proper’ function? The question of multi-functionality or multiple functions (e.g. to exchange gas and to cool the heart) of one organ is also raised in this context. Such investigations must consider the philosophy of science debates on ‘function’ (Krohs and Kroes 2009) and ‘mechanism’ (e.g. Machamer et al 2000) in biology and engineering.

Conclusion and outlook

Conceptual tools derived from engineering design (Pahl et al 2007, Colani et al 2011) prove to be useful in analysing the details of the biomimetic working process. They can be used to systematize and clarify knowledge on different levels. Using these conceptual tools, it becomes clear what ‘functions’ and ‘working principles’ represent in the biological or engineered system under consideration. Furthermore, it becomes evident what, in fact, is transferred from the biological model to the technical application. If biomimetics is to be considered a self-contained science (instead of an auxiliary tool that solely deals with extracting exploitable knowledge from biological examples), then its area of research concerns the functions and working principles found in living systems that potentially can be utilised in engineered constructions. Vandevenne et al (2016) seem to use a related approach to that presented here. Their ‘genealogy trees’ with respect to functions (Verhaegen 2013) and working principles do, however, differ from what is mentioned above. This is probably due to their direct interest in applications and not, as here, in the theoretical underpinnings of biomimetics. The engineering design schema can, however, also be used to systematize knowledge in biomimetics and as a heuristic tool in concrete biomimetic projects. It clearly points to the important issues that remain to be investigated and provides a common ground for interdisciplinary communication.

It also becomes clear that most biomimetic projects use only one particular function of an organism together with an associated working principle. Any biological function, however, is a single entity within a complex web of functions that is characteristic for a particular group of organisms. A key property of organisms is that all those functions, and thereby also the constructions that embody them, work together in a system. Biological ‘constructions’ are also often multifunctional. An eggshell, for instance, has a static function and not only allows for gas exchange, but also protects the embryo from microorganisms. Such multifunctional features can be covered by the here-developed conceptual schema.

This account provides an integrative and comprehensive approach that comprises the working process from biological models to engineered products. Our approach has the advantage that the well-developed body of knowledge from engineering design (only touched upon here) can be utilised as a conceptual tool in biomimetics. The engineering distinction between the level of function (that refers to some task) and the level of working principle (that refers to cause and effect) is useful. In the form-function-relationship, the working principle must be considered as a connector between form (construction) and function. Whether or not the terms ‘function’ and ‘working principle’ from engineering design are well chosen for this distinction is a secondary matter. Importantly, the concept of function is defined differently and non-uniformly in biology. In German texts on biomimetics (Bionik), the term functional principle (Funktionsprinzip) is often used (e.g. Nachtigall 2010). The term working principle (Wirkprinzip, a term without any proper English translation), however, seems to be better suited to distinguish it from the function level, because working principle does not refer to anything that needs to be aimed at: it simply reflects the level of cause and effect.

The schema from engineering design (figures 1 and 3) is also interesting with respect to biological theories. The conceptual levels can serve as a useful tool for investigations in ecomorphology (see e.g. Betz 2008) and ecological biomechanics (see e.g. Denny 2012). The exact relationships, e.g. between function in the engineering sense and the concept of a ‘biological role’ (Bock and von Wahlert 1965), need to be investigated in more detail. Further questions arise also with respect to the theory of evolution, such as whether selection is working on the task level or on a particular function.

The interplay between functions and working principles requires further exploration. Clearly, not every working principle can serve every function, e.g. electromagnetic induction (as a working principle) is useless to generate lift (function) in an aeroplane. Certain constraints are in place, and investigations in this direction are necessary to uncover such details. This is particularly relevant when building ontologies (in the informatics sense of the word; see Smith 2003, Vincent 2014) that connect functions and working principles. The web of functions naturally lends itself as a good starting point for a formalisation in the form of an ontology. Such an ontology will be a useful tool for systematizing knowledge in biomimetics and serve as a basis for further theoretical considerations.

We present the proposed schema using examples of solid constructions—an area into which many biomimetic applications fall. This schema can, however, also be applied to ‘constructions’ in a broader sense, involving biomimetics in the areas of processes and information. Researching and determining parameters and boundary conditions (as performed on the construction level in the above schema, on both the biology and the engineering side; see figures 1 and 3) is relevant beyond constructional biomimetics.

In summary, the conceptual framework from engineering design provides a very useful tool for understanding biomimetics. The levels in the schema allow for a concise systematisation of knowledge not only from a static, but also from a dynamic perspective, i.e.
over time along a biomimetic working process. Moreover, the framework helps integrate knowledge and concepts from various fields outside of engineering, such as morphology or philosophy of science. Beyond clarifying concepts that are relevant for the biomimetic working process, another important element in the knowledge transfer is also integrated, namely graphical representations. This framework is also a good means for raising more theoretical questions and thereby helping to develop a solid basis for biomimetics as a science.

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