Modeling biological inspiration for innovative design

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Abstract

Biomimetic design attempts to use organisms, systems or phenomena from nature as a source of inspiration for new ideas or concepts. Although many human designs take inspiration from the natural world, the interest for systematizing this approach is relatively recent and need a more rigorous analysis in order to be applied in industrial research and development innovative contexts. This paper presents a model for biologically inspired design based on the framework of the C-K design theory. This model was elaborated using a sample of biologically inspired examples from the scientific literature. The results of this analysis reveal the main roles or biological knowledge in the design process: it expands the knowledge space, by means of the differences between natural systems and human-designed systems and also the concepts space, by indicating directions that were not previously exploited in a human design. This research also highlights the new forms of knowledge management and design organization that the systematic use of biological knowledge will require.

Keywords:
biologically inspired design, bioinspiration, biomimetics, C-K theory

1. Introduction

Analogies can be used during the idea generation process, one of the first stages of the design process. They involve the use of similarities between different situations for transferring knowledge across concepts and domains, for problem solving and reasoning and for representing systems (Gentner, 1998). Studying the roles of analogy in design can be useful for better understanding the design process and to find new ways for improving it.

Numerous applications of the analogy process can be found in the biologically inspired design field, which attempts to use the knowledge from the study and observation of natural systems as an analogical source for improving human-made technology. Kalogerakis et al. (2010) affirm that literature on this field "clearly focuses on describing inventive analogies". The analogy-making process of biologically inspired design has been analyzed in terms of the

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similarity between the biological knowledge and the solutions elaborated for a problem based on this knowledge (Mak and Shu, 2004; Helms et al., 2009), and also in terms of the roles of analogy in the design process: Vattam et al. (2010) identified three uses of analogies in the biologically inspired design,"solution generation, evaluation and explanation" and other authors studied how to support the "transfer" process (Sartori et al., 2010; Nagel et al., 2010).

Although these studies allow a better understanding of the biologically inspired design process, they do not fully explain how biological inspiration could be developed as an efficient component for cooperative innovative design, mainly considering its application in the context of research and development in companies. The purpose of this paper is to capture a more systematic modeling of the biologically inspired design that can lead to an implementation in a company context for developing innovative concepts.

The reminder of the paper is organized as follows: Section 2 contains a brief literature review of biologically inspired design, including definitions and methods for application, Section 3 describes the research methodology used for this study, Section 4 details the modeling of the inspiration process of selected case examples using a framework based on the C-K theory, Section 5 presents a discussion on the findings of this modeling and Section 6 concludes the paper indicating perspectives for future work.

2. Theoretical background

This section presents a review of the main definitions and the methods for applying bioinspiration described in the literature.

2.1. Bioinspiration definitions

The use of nature as a source of inspiration for developing new concepts for human conceived systems has occurred throughout human history. Systematic studies on how biological knowledge could improve idea generation are relatively recent: the terms used to characterize this process, such as bionics or biomimetics were only coined in the 1960s.

Jack Steele, from the US Air Force used the term *bionics* in 1960 to describe "the science of systems which have some function copied from nature, or which represent characteristics of natural systems of their analogues". 'Biomimetics' was first used in 1969, in the title of a paper from Otto Schimitt (*Some interesting and useful biomimetic transforms*). The definition of biomimetics first appeared in 1974 in the Webster's dictionary, describing biomimetics as "the study of biological materials, mechanisms and process for synthetizing similar products by artificial mechanisms which mimic natural ones"(Vincent et al., 2006).

Besides bionics and biomimetics, *biomimicry* is another term used to refer to the notion of using inspiration from nature in the design process. This term was popularized by the book of Janine Benyus (Benyus, 1997).

Bioinspiration can be found in different domains such as architecture, lightweight construction, materials, surfaces and interfaces, optimization, information processing, communication and sensorics, robotics and fluid dynamics of swimming and flying (Speck and Speck, 2008).

Table 1: Steps for top-down and bottom-up biomimetic approaches for NPD, as defined by Helms et al. (2009) and Speck and Speck (2008)

	Bottom-up		**Top-down**
Starting point	Fundamental research (biologists)	Starting point	An engineering problem
Research	Understanding the biological model	Search for analogies	Analogy search in biological knowledge
Principle extraction	Identification of "principles" in the biological models	Selection of suitable principles	Suitable principles of one or more biological models analyzed
Abstraction	Transforming the biological principle in a "solution-neutral form"; reframing the solution for engineers understanding and investigation of the potential for technical implementation	Abstraction	Transforming the biological principle in a "solution-neutral form" and reframing for engineers understanding
Development	Technical implementation of the biological principle extracted	Development	Technical implementation of the biological principle extracted

The use of natural phenomena during the design process, do not imply the need of an identical mimic of the natural system, as the terms biomimicry or biomimetics may indicate. The transfer is "hardly ever a direct copy of the biological solution" (Martone et al., 2010) and is claimed to represent a "reinvention inspired by nature" (Speck and Speck, 2008).

Many reasons are evoked for searching inspiration in nature for design: some authors consider nature's solutions inherently superior to human solutions as these solutions are the result of an evolutionary process: "after 3.8 billion years of evolution, nature has learned: what works, what is appropriate, what lasts" (Benyus, 1997), "natural materials have evolved over a very long period of time [...] if a natural material does a better job than an existing synthetic counterpart then biomimicry of that material should be considered" (Reed et al., 2009). Other authors consider that differences between nature and technology transform nature in a useful source of inspiration for technology development (Vogel, 2003). However, as highlighted by Goncalves et al. (2012), making use of sources of inspiration is not a guarantee for creative and successful outcomes of the design process.

2.2. Biologically inspired design

Vincent et al. (2006) indicated that "no general approach has been developed for biomimetics". Nevertheless, some attempts of systematization and understanding of this process have already been made.

When considering the biomimetic design process as a whole, from the initial idea to the final product, two directions were identified (Speck and Speck, 2008; Helms et al., 2009): the *bottom-up* approach (also named "solution-driven" or "biology push") and the *top-down* approach (also named "problem-driven" or "technology pull"). The steps for each of these directions, can be summarized as indicated in table 1.

Helms et al. (2009) observed that in real design situations, these steps for bottom-up and top-down processes do not occur sequentially. Speck and Speck (2008) also observed that in the top-down approach, the search for biological analogies may also indicate some lack of fundamental biological data, which can trigger a knowledge extension process, called "extended top-down process". The same iterative process can also come from a bottom-up process, as shown by Hesselberg (2007), in the so-called "integrative organism-driven biomimetic approach". In both approaches, the "principles" discovered from the biological models are used as insights for concept generation and product development.

These two directions also have common features with the conceptual design phase of systematic design (Pahl and Beitz, 1984), such as the identification of functions and sub-functions of a system and the search for solution principles in order to generate concepts (Sartori et al., 2010). A broader definition of the role of biological knowledge in the conceptual design step of systematic design is as analogies in the idea generation process for solutions search (Smith, 1998; Mak and Shu, 2008; Wilson et al., 2010; Vattam et al., 2010), meaning that a "transfer" takes place.

The effect of biological examples, which can be considered as distant analogies, in idea generation during the conceptual design was the object of a cognitive study (Wilson et al., 2010). The results of this study revealed that biological examples indeed increased novelty although not significantly affecting the variety of ideas generated, when compared to a situation with no examples. The use of human-engineered examples in the idea generation process had a similar effect on the novelty increase, but the variety decreased, which could indicate greater fixation effects caused by these human-engineered examples.

2.3. Methods to support biologically inspired design

Shu et al. (2011) identified two directions for research on methods to support biologically inspired design: the first one related with the "search, retrieval and representation of the biological phenomena for design" and the second one related with "better understanding and support the application of biological analogies to design".

The first direction, related to the search, retrieval and representation of biological phenomena for design, include methods such as the integration of biologists in the design process, as proposed by the *Biologists at the Design Table* scheme (Peters, 2011), or the development of databases that contain biological phenomena. One online accessible database is the AskNature database (`http://www.asknature.org`), a project of the Biomimicry Institute, which has a structure composed of group functions, sub-groups and functions. Queries for searching the database are formulated using the question *"How would nature ...?"* (e.g. "How would nature control temperature?"). There is also the possibility of searching by the biological phenomena or living system, e.g. "photosynthesis", "lotus leaf".

Databases are dependent on the amount of information entered on it and sometimes the keywords used for queries may be misleading (Shu et al., 2011). In order to attenuate this limitation, an approach using keyword search on texts written on natural-language format, e.g. biology books, scientific communications and papers, was developed (Shu, 2010). Difficulties for the application of this method reside on management of the quantity and the quality of the matches and on the fixation effects that biological examples may induce in designers (Shu et al., 2011; Mak and Shu, 2008).

TRIZ tools have also been used for facilitating the comprehension of biological systems by engineers and the problem-solving activity. The Bio-TRIZ approach (Vincent et al., 2006) proposes a new contradiction matrix based on biological phenomena as a way of stimulating the transfer between biology and engineering. Hill (2005) uses TRIZ for framing the problem and develops catalog sheets of biological systems basic functions for identifying similarities between biological structures and the contradictions to be solved. Helfman-Cohen et al. (2011, 2012) use other TRIZ tools such as "the law of system completeness" and the "substance-field analysis" for acquiring a better understanding of biological systems thus facilitating the transfer from biology to engineering.

The second direction, related to supporting the application of biological analogies for design, has studies on the cognitive process of biologically inspired design (Helms et al., 2009; Vattam et al., 2010). These studies aim at understanding the conditions for use and contents of analogies during the whole design process (including the idea generation). Other studies have focused on the transfer process during biomimetic design process, using tools such as the IDEA-Inspire software to facilitate the use of biologically inspiration for idea generation (Chakrabarti et al., 2005) and the SAPPHIRE model for understanding biological systems (Sartori et al., 2010). This last study could also be included on the first direction. The model developed by (Nagel et al., 2010), include representing the biological systems using functional models for facilitating the transfer between biology and engineering, but the efficiency of this method depends on the database of biological phenomena and on the designer's skills.

2.4. Conclusions from the theoretical background and research question

This literature review on biomimetic design showed the main research directions in the field. Many authors recognize that identical mimicking of natural systems is very unlikely, and that nature should be seen as a source of inspiration (Vogel, 2003; Speck and Speck, 2008; Martone et al., 2010).

Considering the whole biomimetic design process, two directions were identified: top-down and bottom-up. In the first one, an engineering problem triggers the quest for biological solutions that could be helpful for solving the problem, in the second one, the study of biological phenomena reveals some interesting property that could be useful for technical applications. In both cases, inspiration from nature is seen as a transfer between biology and engineering domains for generating ideas.

Another research direction is on methods that support biologically inspired design, that aim to ease the search and retrieval of biological phenomena that could be relevant for solving a design problem and also to facilitate the use of biological analogies in design. The content of the transfer from the biological phenomena and the process for retrieving "inspiring" biological phenomena have also been studied in literature for helping in the integration of biological inspiration to the design process.

These studies represent a first step towards the systematization of biomimetic design method, however, the reasons for using biological knowledge are not fully explained in these texts. Based on this conclusion our main research question is formulated:

RQ: Why seeking inspiration in nature for design?

A subsidiary question also studied is *How does bioinspiration work?*.

Exploring this research question involved the study of three selected case examples which were supported by scientific publications accounting for the detailed bioinspiration process.

3. Methodology

The core basis for the search of bioinspiration examples used in the present work were the journal Bioinspiration and Biomimetics (IOP publishing) which contains bioinspired work from different fields of research (robotics, materials, architecture, construction, etc.) and is the journal publishing the greatest numbers of papers on biomimetics per year (Lepora et al., 2013), the review on biomimetics edited by Y. Bar-Cohen (Bar-Cohen, 2012), which has a chapter dedicated to biomimetic products (Masselter et al., 2012) and the review of biomimetic examples by Bhushan (2009).

The analysis of the bioinspiration process of these examples needed a theoretical framework for explaining the inspiration process and how this inspiration lead to a solution. Design theories could be this support as they capture the specificity design reasoning and have already been applied as theoretical frameworks for studying other design issues such as: fixation effects (Agogue et al., 2011; Hatchuel et al., 2011) or creative concept generation (Taura and Nagai, 2013).

Among design theories such as the General Design Theory (GDT), the Axiomatic Design (AD), the Coupled Design Process (CDP) or the Infused Design (ID), we have chosen as the theoretical framework for the examples analysis the C-K design theory (Hatchuel and Weil, 2003). This choice relates to the fact that C-K theory "attempts to improve our understanding of innovative design", allowing the modeling of the generation of new objects (Hatchuel et al., 2012) and also gives knowledge a wider variety of roles in the design process, not only restricting it to being a space of solutions. This is important for biologically inspired design, as in the greatest majority of studies, the biological knowledge is frequently associated with the solutions space (Helms et al., 2009; Speck and Speck, 2008; Farel and Yannou, 2013). The analytical power of the C-K theory for the innovative design has been confirmed by existing literature (Reich et al., 2012; Ullah et al., 2012). Moreover, C-K theory has been used to model creativity process in industrial R&D (see Hatchuel et al. (2012) for examples).

3.1. Principles of C-K theory

C-K theory was introduced in 2003 by Hatchuel and Weil. In this theory, design is defined as "an interplay between two interdependent spaces", the space of concepts (C) and the space of knowledge (K). Space K contains the available knowledge. Space C contains propositions, called concepts, that are "neither true nor false in K about partially unknown objects x". Design proceeds by the expansion of this initial concept into other concepts (by partitioning the concept) and/or into new knowledge. In this way, in C-K theory, both C and K spaces are expandable and these transformations between spaces and inside the same space are called "operators". There are four operators in C-K theory: C→C, C→K, K→K and K→C. The design solution is the "the first concept to become a true proposition in K" (a conjunction).

These two spaces have different structures. As in C-space only partitioning or inclusion are allowed, this space has a tree structure, in which each node represent a partition in several sub-concepts. The K space grows like "an archipelago": new propositions are added without necessarily following a stable order or being connected directly (Hatchuel and Weil, 2009). Figure 1, summarizes the operators and the main features of the C-K theory.

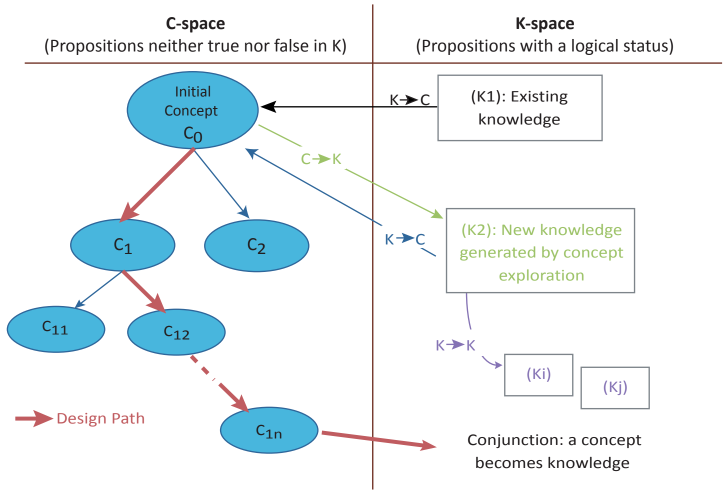

Figure 1: C-K diagram and operators (adapted from Hatchuel and Weil (2003, 2009); Hatchuel et al. (2012))

The theory proposes two types of partitioning for concepts: *restrictive* partitions and *expanding* partitions (Hatchuel and Weil, 2003). The restrictive partitions add a property to a concept already known as a property of the entities concerned. The expanding partitions add properties not known in K as a property of the entities concerned. Therefore, "creativity and innovation are due to expanding partitions of concepts".

4. Case examples bioinspiration modeling

For the study of the bioinspiration process, we have detailed three examples, which are described in biomimetic literature. Two of them were subject of articles of the journal Bioinspiration and Biomimetics (Lienhard et al. (2011) –Flectofin®, Solga et al. (2007) – the lotus effect). The third one was cited by Bhushan (2009) on its review on biomimetics and is the object of a great number of publications in the biomimetic literature.

4.1. Self-cleaning surfaces inspired by the lotus-effect

During their works on the study of leaf surfaces by scanning electron microscopy (SEM), Barthlott and Neinhuis (1997) observed that cleaning the leaves before examination was always necessary for "plants with smooth leaves surfaces" while those with "epicuticular wax crystals were almost completely free of contamination". These epicuticular wax crystals were well known for conferring water repellency. Moreover, studies on the relationship between particle deposition and surface roughness had already been made. These authors observed that the idea of a correlation between water repellency and reduced contamination already existed, but lacked experimental data for consolidation.

Barthlott and Neinhuis used the observation of the lotus leaves to elaborate a model explaining the relationship between surface roughness, particle removal (self-cleanliness) and wettability. In particular, the result of this work was patented for application in human-made surfaces (Barthlott, 1998; Barthlott and Neinhuis, 2000). The surfaces were rendered self-cleaning and hydrophobic by having a structure of elevations and depressions made of hydrophobic polymers or materials.

The Lotus-effect mechanism was used for the development of exterior coatings such as Lotusan (Sto Corp.), used for façade protection (Bhushan, 2009). It has also been introduced in fabrics by immobilizing hydrophobic silica particles functionalized with vinyl groups using UV photo-grafting over a poly lactic acid (PLA) fabric. In the process a rough surface with superhydrophobicity is created, thanks to the silica particles and the vinyl groups (Singh et al., 2012). Considering the two biomimetic approaches described in the theoretical background of this paper, the products developed based on the Lotus-effect were the result of a bottom-up approach, in which the biological phenomena triggered the search for potential technological applications. Seen from a C-K perspective, the first studies of Barthlott and colleagues on leaf surfaces formed a knowledge base on these biological structures. The observation of an interesting property during the construction of this knowledge base, the non-contamination of the leaves with epicuticular wax crystals led to the formulation of an expanding partition for the concept of self-cleaning surfaces: "with a rough surface" (opposed to rendering smooth surfaces self-cleaning). The study of the lotus model, activated the traditional knowledge base on the "behavior of liquids applied to solid surfaces" and allowed to explain the reasons for obtaining the lotus effect: rough surfaces with hydrophobic coatings. The products with the lotus-effect were then developed using systematic engineering design (embodiment design, detail design): façade paints with nanostructured materials (Lotusan), fabrics, etc. This process is schematically represented in Figure 2.

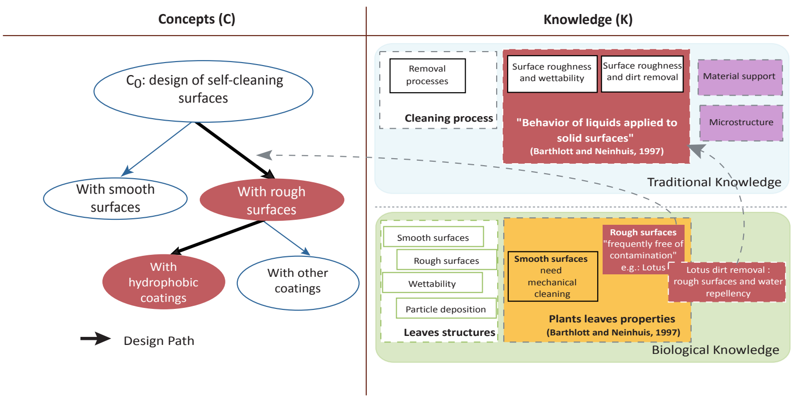

Figure 2: C-K diagram for the self-cleaning surfaces example

4.2. Development of a hingeless flapping mechanism inspired by the bird-of-paradise

Reducing the complexity of movable building structures, such as façade shading systems is a challenge for architecture (Knippers and Speck, 2012). The technical hinges used in blinds and umbrellas for deployability are subjected to constant load cycles that wear the mechanical pieces and cause the need of constant maintenance (Lienhard et al., 2011). From the observation that among plants there are hinge-free movements and reversible deformation principles, an "interdisciplinary research collaboration" between architects, engineers and biologists from the Institute of Building Structures and Structural Design (IKTE) of the University of Stuttgart and the Plants Biomechanic Group of the University of Freiburg began. This collaboration aimed to investigate how these plants could be used for developing technical applications (Masselter et al., 2012).

During this research, a screening process on plant movements led to the identification of a kinematic principle for a façade shading system. This principle was found on the perch of the 'bird of paradise' (*Strelitzia reginae*) flower. This perch remains closed by its two adnate petals protecting the flower's reproductive organs. Birds wishing for the nectar of the flower land on the perch, bending it down. This bending simultaneously unfolds the petals allowing pollen to touch the bird, ensuring pollination (Knippers and Speck, 2012).

Biologists investigated further this mechanism and the flower structure. A physical model that had a similar behavior was built, by attaching perpendicularly a thin shell element (*the fin*) to a rib (*the backbone*). Bending the rib causes a bending motion of the shell by "torsional buckling". The *Strelitzia reginae* mechanism was the element that showed how using this torsional buckling was possible, as buckling is usually considered as a material failure mode. In the next steps, studies on possible configurations of the rib-shell element were carried over, and some adaptations of the observed principle to the physical structure were made: stiffness adaptations, stress reduction and materials choice (Lienhard et al., 2011). The result of this development process was a patented façade shading system called Flectofin® (Schleicher et al., 2011).

Seen using a C-K perspective, summarized in Figure 3, the existing knowledge about deployable systems in architecture, using hinges and rollers, have triggered the generation of the initial concept for architects. The search for alternatives to these systems led the research group to the activation of the biological knowledge on plants movements, which had an unexpected property: some plants had deployable mechanisms without hinges. This generated an expanding partition to the initial concept: "without using hinges".

The search for new attributes to this concept, led to the expansion of the knowledge on plant deformation avoiding hinges. Several mechanisms were studied, i.e. they were interpreted considering existing knowledge, using for example 2D or 3D models. The main knowledge base activated was about reversible elastic deformations of materials. During this study on the reversible deformation mechanisms of plants, the pollination mechanism of the bird of paradise was identified as being a "special form of lateral torsional buckling" (Lienhard et al., 2011). This knowledge, referred to a known knowledge base about a material deformation process, but it revised the traditional way of perceiving this knowledge, changing it from a failure mode to a desirable property.

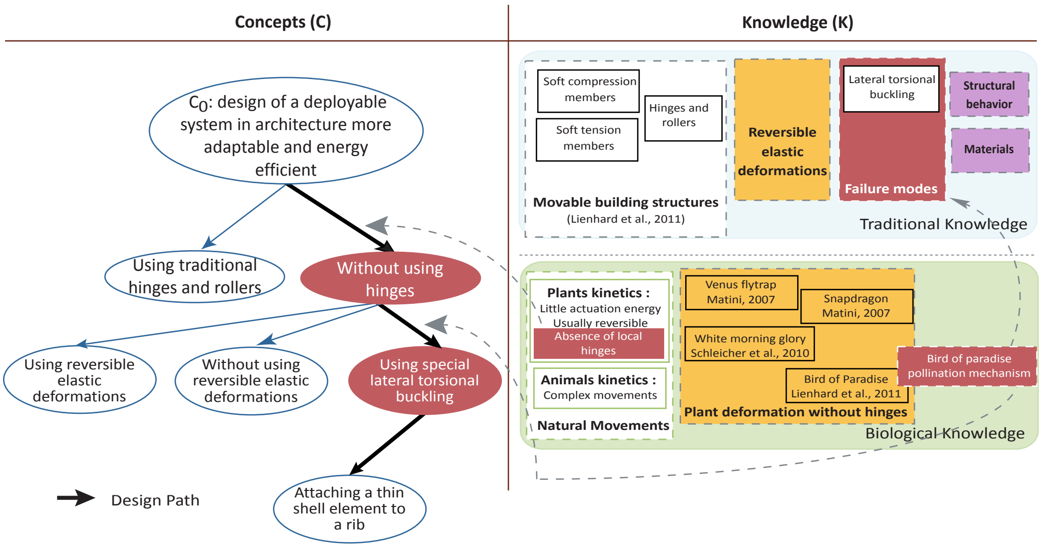

Figure 3: C-K diagram on deployable systems in architecture (inspired by plants kinetics)

The concept "without using hinges", could then be partitioned into: using the special form of lateral torsional buckling, that led to expansions on the traditional knowledge bases, to conceive and test a physical model that would have the special form of lateral torsional buckling. The next steps correspond to traditional engineering steps, where the possible structural configurations and the structural behavior were modeled and tested, the materials chosen, etc.

4.3. Development of gecko-inspired adhesives

The most common man-made adhesives use wet adhesives for the attachment of two surfaces (Bhushan, 2009). Geckos have "strong, high repeatable, high speed and controllable attachment and detachment capabilities on a wide range of smooth and slightly rough surfaces" (Menguc et al., 2012), which had already been observed by Aristotle two millennia ago (Autumn and Peattie, 2002).

These controlled adhesive properties of geckos, unmatched by human-made adhesives, stimulated researches to explain the "secret of geckos' adhesive capabilities" (Autumn and Peattie, 2002). Some hypothesis for the gecko's attachment included suction, friction or intermolecular forces (Autumn et al., 2000). These authors revealed that the attachment properties of gecko were linked to van der Waals forces (intermolecular forces) between setae (keratinous hairs covering gecko's toes) and the surface. They also showed that that the gecko's toe uncurling and peeling movements also contributed to the adhesive properties of setae.

This knowledge about the adhesion properties of geckos has stimulated research on gecko-inspired adhesives. One direction of these researches aims at fabricating micro and nanostructured fibrillar surfaces – e.g. the review of fabrication approaches of gecko-inspired surfaces by Boesel et al. (2010) – that could have reversible dry-adhesion properties (Bhushan, 2009). Applications of these adhesives include clean transportation during the assembly process and biomedical skin patches (Kwak et al., 2011).

Nevertheless, Bartlett et al. (2012) indicate that these attempts have poor adhesive properties at large length scales, and used the knowledge acquired with the studies on gecko's adhesion to develop a scaling theory that allowed the development of "reversible, hand-sized synthetic adhesive structures with unprecedented capacity, even without fibrillar features".

Using C-K theory for analyzing this case, illustrated in Figure 4, the starting point was the biological knowledge about the gecko, which had interesting abilities. The initial concept could be interpreted as the "design surfaces with strong and controllable adhesive properties". This stimulated a deeper research for understanding the gecko's adhesion phenomena. This research represent an expansion of the biological knowledge about gecko's adhesion and activated traditional knowledge bases on the mechanisms for adhesion, such as suction, friction and intermolecular forces. The measurements by Autumn et al. (2000) showed that the adhesion mechanism was linked to the setae and the van der Waals forces. This allowed the partitioning of the initial concept on "using fibrillar structures in the surface", which led to the development of fabrication techniques and surfaces using this kind of surface pattern for adhesion. The other partition of this concept could then be formulated as: "without using fibrillar structures".

As these artificial fibrillar structures were not adaptable to larger scales, Bartlett et al. (2012) developed a "scaling theory", which used the knowledge about the energy balance of a material adhering through a given surface area, and led to the development of un-patterned surfaces with reversible controllable adhesive properties, which represent a partitioning of the concept "without using fibrillar structures".

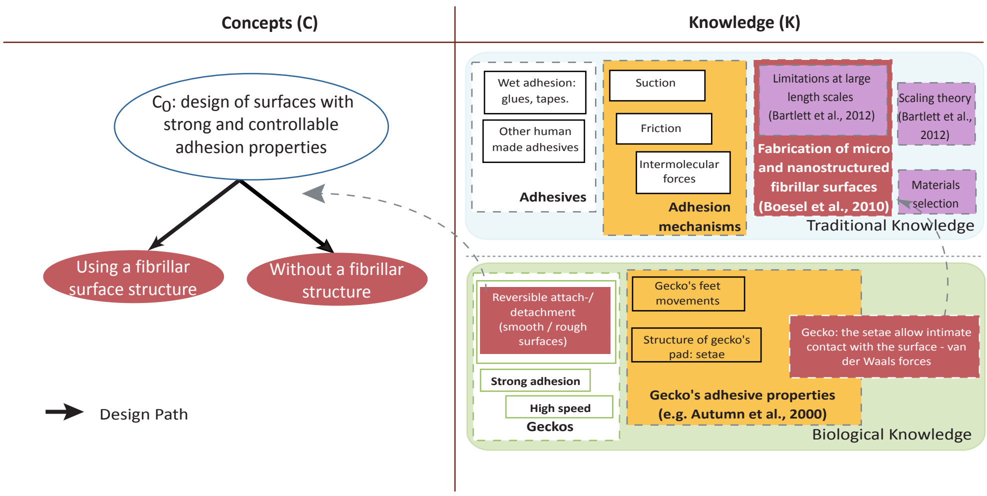

Figure 4: C-K diagram for gecko inspired adhesives

5. Discussion

In the previous three examples, bioinspiration is a part of the design process. The final products have, however, no or little similarity with the biological inspiration source, in terms of materials, forms or processes.

These examples highlight the roles of biological knowledge in the design process: In the gecko and the lotus case, the biological knowledge indicated an unexplored path for product development, or in the C-K theory terms, led to a partition on the concepts space, with the formulation of a new concept. This partition on the C space is an expanding partition, since it triggers an expansion of the knowledge bases: new knowledge were necessary to explain the lotus and gecko phenomena and traditional knowledge bases were revised.

For the Flectofin® case, the starting point was a design problem, which activated the biological knowledge bases. This biological knowledge about the plants movements had the same role as in the lotus and gecko case: it helped formulating an expanding partition in the concepts space (without using hinges), and this partition guided the expansion on the knowledge space: more knowledge on different biological models was necessary, and explaining the observed natural phenomena required the activation of traditional knowledge bases that would not otherwise be activated.

Based on these observations, a model for bioinspiration can be proposed, using a C-K framework:

Step1: The activation of biological knowledge occurs when traditional design paths seem to be blocked. In this case, the biological knowledge can have an unexpected property considering the existing traditional knowledge that helps partitioning a concept or formulating a new initial concept.

Step2: This concept partitioning triggers an expansion of the knowledge on biological systems (screening different systems, explaining observed phenomena). This expansion in biological knowledge is accompanied by an exploration of the traditional knowledge base for explaining the biological phenomena. These traditional knowledge bases can belong to designers, or can come from other domains or may be completely unknown, requiring other knowledge expansions. In all cases, some unexpected properties of biological phenomena, which oblige the revision of traditional knowledge, using non-spontaneously activated knowledge will be identified.

Step3: These unexpected properties triggers concepts partitioning and guides knowledge exploration.

Step4: Once the bioinspired path is identified and the traditional knowledge bases activated, the design process continues, using the new elements gathered with the bioinspiration process.

This model is schematized in Figure 5.

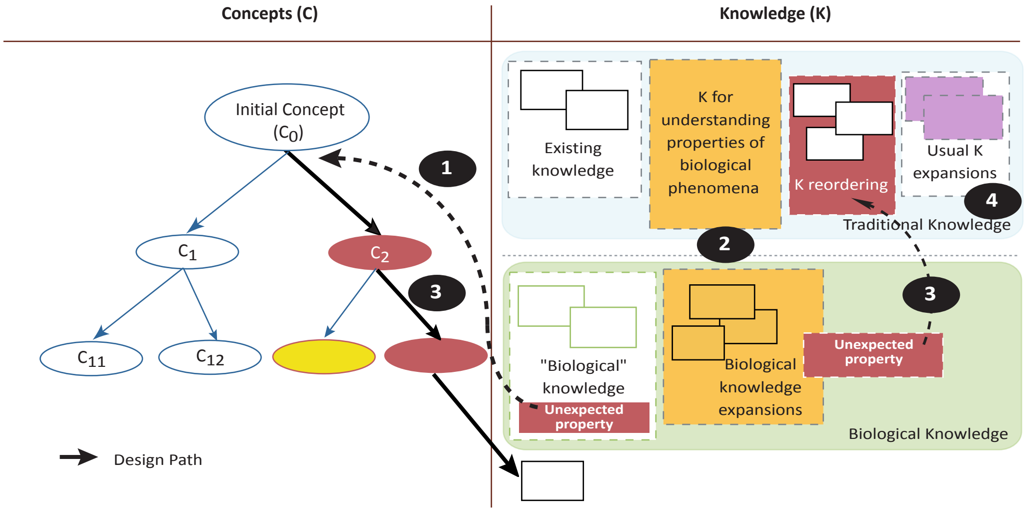

Figure 5: C-K diagram for bioinspiration

Our research questions can be answered using the proposed model: bioinspiration is used when traditional design paths seem to be blocked, or when nature has properties that are not explained by the traditional knowledge bases. The bioinspiration process uses the unexpected properties of biological knowledge for concepts partitioning and for knowledge revision and expansion.

Considering the top-down and bottom-up directions proposed by the literature, the C-K model for bioinspiration shows that the principles extracted from biological knowledge (Speck and Speck, 2008; Helms et al., 2009) consist in properties that are unexpected considering the traditional knowledge bases. In addition to generating new concepts, these unexpected properties also allow a revision of the traditional knowledge, including the activation of non-spontaneously activated knowledge, which is not a simple knowledge transfer between the biological and traditional bases. Table 2 compares the top-down, bottom-up and C-K bioinspiration models. Although containing similar steps, the bioinspiration C-K model highlights the different roles of biological and traditional knowledge during the design process.

This model also brings some insights about the creativity outcome of using analogies between concepts from distant domains, such as biology and engineering, during the design process. According to Cheong and Shu (2013) these analogies are considered as stimuli to creative ideas. The bioinspiration modeling shows that the distant analogy is useful for concept generation when it allows a dual expansion: An expansion of the inspiring knowledge and an expansion of the traditional knowledge. This dual expansion enlarges the knowledge bases available for design and the unexpected properties found during this expansion process increase the possibilities of concepts partitioning.

Table 2: Comparison between bioinspiration C-K model, bottom-up and top-down biomimetic approaches

Bioinspiration C-K	**Bottom-up**	**Top-down**
Blocked design paths (C-space) Biological research (K-space)	Fundamental biological research	An engineering problem
Identification of unexpected properties of biological knowledge (K-space) and C-partitioning (C-space)	Understanding the biological model and principle extraction	Analogy search in biological knowledge and selection of suitable principles
Further exploration of biological knowledge (unexpected properties) and revision of traditional knowledge bases (K-space)	Separation of the principles from the biological model, transfer of knowledge. Abstraction – (Speck and Speck, 2008)	Separation of the principles from the biological model and transfer of knowledge. Abstraction – (Speck and Speck, 2008)
Concepts partitioning using the revised traditional knowledge and the unexpected properties	Making principles understandable by non-biology experts and problem definition	Making principles understandable by non-biology experts
Definition of design paths developed with traditional and revised knowledge	Technical implementation of the biological principle extracted	Technical implementation of the biological principle extracted

6. Conclusions and future work

Using biologically inspired design in a systematic way for improving the design process and generating new and innovative ideas has received great interest since the 1960s. The first steps for systematizing this process include the development of databases with biological phenomena, the use of tools for facilitating the analogical transfer between biology and engineering, and studies focusing on understanding the effects of these analogies on idea generation.

The proposed modeling of some examples of bioinspiration using the C-K theory framework provide a new insight about the role of bioinspiration in the design process and also on the new tools that bioinspiration requires when applied in a company context.

Bioinspiration occurs when traditional design paths seems to be blocked. Nevertheless, the partitioning indicated by the unexpected property from biological knowledge may seem not feasible, just being a surprising concept. Accessible new design paths can result from this process, when subsequent expansion of biological knowledge indicate that a revision of traditional knowledge base is required (expansion or discovery processes).

Therefore, biological knowledge does not offer solutions, it stimulates the reorganization of knowledge bases, creating bridges between different domains inside the traditional knowledge. This conclusion is important for reducing the risks of idolizing nature processes and systems.

Systematically applying bioinspiration in companies requires a new form of knowledge management, which allows the revision and expansion of traditional knowledge, in the light of the interesting properties gathered from biological knowledge. The acquisition of biological knowledge stimulates the identification of an *unexpected property* when this knowledge is compared to the traditional knowledge available. This unexpected property will thus revise and expand the traditional knowledge. This expansion can lead to new paths that may be very distant from the initial unexpected property, but that will benefit from the revised traditional knowledge bases for their development. Applying bioinspiration in a company context requires not only new competencies in biology, but also the possibility of traditional knowledge expansion.

On-going experimentations for applying bioinspiration for generating new concepts in a large automaker research and development process show that one of the greatest difficulties for the bioinspiration process is finding the suitable biological knowledge bases for the design problem. The methods aiming at systematizing biological models for facilitating analogical transfer, such as those developed by Helfman-Cohen et al. (2011, 2012) can help overcoming this difficulty.

In the first steps of this concrete field study under development, the application of bioinspiration led to the identification of potentially interesting biological properties coming from unusual domains considering the traditional engineering competencies. A deeper exploration of this new biological knowledge required the association with a biology specialist. The exchanges between this specialist and the engineers showed some possibilities of rediscussion of the traditional engineering knowledge and also that new competencies had to be developed inside the company. These interactions also reveals some approach and communication differences between scientists with engineering and biology backgrounds. The need for further exploration of biological knowledge for developing concepts associated with the unexpected properties and the reorganization of the existing traditional engineering knowledge were both steps found in the C-K bioinspiration model. Further research should include the evaluation of the organizational and managerial implications of applying bioinspiration in this company study.

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References

Agogue, M., Kazakci, A., Weil, B., Cassotti, M., 2011. The impact of examples on creative design: explaining fixation and stimulation effects, in: International conference on engineering design (ICED'11), Technical University of Denmark.

Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R., Full, R.J., 2000. Adhesive force of a single gecko foot-hair. Nature 405, 681 – 685.

Autumn, K., Peattie, A.M., 2002. Mechanisms of adhesion in geckos. Integrative and Comparative Biology 42, 1081–1090.

Bar-Cohen, Y., 2012. Biomimetics: nature based innovations. CRC press.

Barthlott, W., 1998. Self-cleaning surfaces of objects and process for producing same. patent EP0772514 B1.

Barthlott, W., Neinhuis, C., 1997. Purity of the sacred lotus, or escape from contamination in biological surfaces. Planta 202, 1–8.

Barthlott, W., Neinhuis, C., 2000. Method of producing self-cleaning detachable surfaces. patent WO/2000/058410.

Bartlett, M.D., Croll, A.B., King, D.R., Paret, B.M., Irschick, D.J., Crosby, A.J., 2012. Looking beyond fibrillar features to scale gecko-like adhesion. Advanced Materials 24, 1078–1083.

Benyus, J.M., 1997. Biomimicry: innovation inspired by nature. William Morrow and Co.

Bhushan, B., 2009. Biomimetics: lessons from nature - an overview. Philosophical Transactions of the Royal Society A: Mathematical,Physical and Engineering Sciences 367, 1445–1486.

Boesel, L.F., Greiner, C., Arzt, E., del Campo, A., 2010. Gecko-inspired surfaces: A path to strong and reversible dry adhesives. Advanced Materials 22, 2125–2137.

Chakrabarti, A., Sarkar, P., Leelavathamma, B., Nataraju, B., 2005. A functional representation for aiding biomimetic and artificial inspiration of new ideas. AI EDAM 19, 113–132.

Cheong, H., Shu, L., 2013. Using templates and mapping strategies to support analogical transfer in biomimetic design. Design Studies 34, 706 – 728.

Farel, R., Yannou, B., 2013. Bio-inspired ideation: Lessons from teaching design to engineering students, in: International conference on engineering design (ICED'13), Sungkyunkwan University, Seoul, Korea.

Gentner, D., 1998. A Companion to Cognitive Science. Wiley-Blackwell. chapter Analogy. pp. 107–113.

Goncalves, M., Cardoso, C., Badke-Schaub, P., 2012. Find your inspiration: Exploring different levels of abstraction in textual stimuli, in: Duffy, A., Nagai, Y., Taura, T. (Eds.), Proceedings of the 2nd International Conference on Design Creativity Volume 1, pp. 189–198.

Hatchuel, A., Le Masson, P., Weil, B., 2011. Teaching innovative design reasoning: How concept–knowledge theory can help overcome fixation effects. AI EDAM 25, 77–92.

Hatchuel, A., Weil, B., 2003. A new approach of innovative design: an introduction to c-k theory, in: Proceedings of the 14th International Conference on Engineering Design (ICED'03), Stockholm, Sweden, pp. 109–124.

Hatchuel, A., Weil, B., 2009. C-k design theory: an advanced formulation. Research in Engineering Design 19, 181–192. 10.1007/s00163-008-0043-4.

Hatchuel, A., Weil, B., Masson, P., 2012. Towards an ontology of design: lessons from c-k design theory and forcing. Research in Engineering Design , 1–17.

Helfman-Cohen, Y., Reich, Y., Greenberg, S., 2011. What can we learn from biological systems when applying the law of system completeness? TRIZ future 2011, Dublin, Ireland .

Helfman-Cohen, Y., Reich, Y., Greenberg, S., 2012. Substance field analysis and biological functions. TRIZ future 2012, Lisbon, Portugal .

Helms, M., Vattam, S.S., Goel, A.K., 2009. Biologically inspired design: process and products. Design Studies 30, 606 – 622.

Hesselberg, T., 2007. Biomimetics and the case of the remarkable ragworms. Naturwissenschaften 94, 613–621.

Hill, B., 2005. Goal setting through contradiction analysis in the bionics-oriented construction process. Creativity and Innovation Management 14, 59–65.

Kalogerakis, K., Lthje, C., Herstatt, C., 2010. Developing innovations based on analogies: Experience from design and engineering consultants. Journal of Product Innovation Management 27, 418–436.

Knippers, J., Speck, T., 2012. Design and construction principles in nature and architecture. Bioinspiration & Biomimetics 7, 015002.

Kwak, M.K., Pang, C., Jeong, H.E., Kim, H.N., Yoon, H., Jung, H.S., Suh, K.Y., 2011. Towards the next level of bioinspired dry adhesives: New designs and applications. Advanced Functional Materials 21, 3606–3616.

Lepora, N.F., Verschure, P., Prescott, T.J., 2013. The state of the art in biomimetics. Bioinspiration & Biomimetics 8, 013001.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., Knippers, J., 2011. Flectofin: a hingeless flapping mechanism inspired by nature. Bioinspiration & Biomimetics 6, 045001.

Mak, T., Shu, L., 2004. Abstraction of biological analogies for design. CIRP Annals - Manufacturing Technology 53, 117 – 120.

Mak, T., Shu, L., 2008. Using descriptions of biological phenomena for idea generation. Research in Engineering Design 19, 21–28.

Martone, P.T., Boller, M., Burgert, I., Dumais, J., Edwards, J., Mach, K., Rowe, N., Rueggeberg, M., Seidel, R., Speck, T., 2010. Mechanics without muscle: Biomechanical inspiration from the plant world. Integrative and Comparative Biology .

Masselter, T., Bauer, G., Gallenmuller, F., Haushahn, T., Poppinga, S., et al., 2012. Biomimetics: nature-based innovation. CRC Press. chapter Biomimetic products. pp. 377–429.

Matini, M.R., 2007. Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien. Ph.D. thesis. Institut fur Tragkonstruktionen und Konstruktives Entwerfen (ITKE), University of Stuttgart.

Menguc, Y., Yang, S.Y., Kim, S., Rogers, J.A., Sitti, M., 2012. Gecko-inspired controllable adhesive structures applied to micromanipulation. Advanced Functional Materials 22, 1246–1254.

Nagel, J.K., Nagel, R.L., Stone, R.B., McAdams, D.A., 2010. Function-based, biologically inspired concept generation. AI EDAM 24, 521–535.

Pahl, G., Beitz, W., 1984. Engineering design, a systematic approach. The Design Council.

Peters, T., 2011. Nature as measure: The biomimicry guild. Architectural Design 81, 44–47.

Reed, E.J., Klumb, L., Koobatian, M., Viney, C., 2009. Biomimicry as a route to new materials: what kinds of lessons are useful? Philosophical Transactions of the Royal Society A: Mathematical,Physical and Engineering Sciences 367, 1571–1585.

Reich, Y., Hatchuel, A., Shai, O., Subrahmanian, E., 2012. A theoretical analysis of creativity methods in engineering design: casting and improving asit within c–k theory. Journal of Engineering Design 23, 137–158.

Sartori, J., Pal, U., Chakrabarti, A., 2010. A methodology for supporting "transfer" in biomimetic design. AI EDAM 24, 483–506.

Schleicher, S., Lienhard, J., Knippers, J., Poppinga, S., Masselter, T., Speck, T., 2011. Hingeless, infinitely deformable folding mechanism. patent EP 2320015.

Schleicher, S., Lienhard, J., Poppinga, S., Speck, T., Knippers, J., 2010. Abstraction of bio-inspired curved-line folding patterns for elastic foils and membranes in architecture. Design and Nature V , 479–90.

Shu, L., 2010. A natural-language approach to biomimetic design. AI EDAM 24, 507–519.

Shu, L., Ueda, K., Chiu, I., Cheong, H., 2011. Biologically inspired design. CIRP Annals - Manufacturing Technology 60, 673 – 693.

Singh, A.V., Rahman, A., Kumar, N.S., Aditi, A., Galluzzi, M., Bovio, S., Barozzi, S., Montani, E., Parazzoli, D., 2012. Bio-inspired approaches to design smart fabrics. Materials & Design 36, 829 – 839.

Smith, G.F., 1998. Idea-generation techniques: A formulary of active ingredients. The Journal of Creative Behavior 32, 107–134.

Solga, A., Cerman, Z., Striffler, B.F., Spaeth, M., Barthlott, W., 2007. The dream of staying clean: Lotus and biomimetic surfaces. Bioinspiration & Biomimetics 2, S126.

Speck, T., Speck, O., 2008. Process sequences in biomimetic research, in: Brebbia, C. (Ed.), Design and Nature IV, WIT Press. pp. 3–11.

Taura, T., Nagai, Y., 2013. A systematized theory of creative concept generation in design: first-order and high-order concept generation. Research in Engineering Design 24, 185–199.

Ullah, A.S., Rashid, M.M., Tamaki, J., 2012. On some unique features of c–k theory of design. CIRP Journal of Manufacturing Science and Technology 5, 55 – 66.

Vattam, S.S., Helms, M.E., Goel, A.K., 2010. A content account of creative analogies in biologically inspired design. AI EDAM 24, 467–481.

Vincent, J.F., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A., Pahl, A.K., 2006. Biomimetics: its practice and theory. Journal of The Royal Society Interface 3, 471–482.

Vogel, S., 2003. Nature's swell, but is it worth copying? MRS Bulletin 28, 404–408.

Wilson, J.O., Rosen, D., Nelson, B.A., Yen, J., 2010. The effects of biological examples in idea generation. Design Studies 31, 169 – 186.