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MODELING BIOLOGICALLY INSPIRED DESIGN WITH THE C-K DESIGN THEORY

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1. Introduction

In biologically inspired design, biological processes, structures or mechanisms are used as a source of inspiration for improving technical systems. The systematization of this process has received great interest in the last years, proposing steps for the process, based on designers experience [Biomimicry 3.8 2014] or on cognitive studies using courses on biologically inspired design [Helms et al. 2009], [Goel et al. 2014]. Existing problem-solving methods such as TRIZ have also been adapted to using the natural systems as a source of inspiration [Vincent et al. 2006]. Other tools were developed to facilitate the analogical transfer between a biological system and a technical system, such as databases [AskNature 2013], searches on broader sources such as biology literature [Shu et al. 2011], on patents [Verhaegen et al. 2011] and on the Internet [Vandevenne et al. 2012]. Other approaches for representing and retrieving biological phenomena include functional and structural analysis [Nagel et al. 2010], [Helfman-Cohen et al. 2012] and computational tools [Sartori et al. 2010], [Wiltgen et al. 2011]. Our aim in this paper is to expand the analysis on the process of biologically inspired design by capturing the interactions between biological and traditional knowledge and the generation of bio-inspired concepts during this process, using the C-K design theory framework. The analytical power of this theory has been confirmed by existing literature, for example, Reich et al. [2012] use the theory for analysing a creative method and Hatchuel et al. [2011] for analysing fixation effects.
The remainder of this paper is structured as follows. In Section 2 we present the theoretical background on biologically inspired design and our research questions. In Section 3 we detail the methodology used and present the fundamentals of the C-K design theory that will support our analysis. In section 4 we present the case examples of biological inspiration and their modelling using the C-K theory. Section 5 discusses the results of the modelling and Section 6 concludes the paper.

2. Biologically inspired design: Definitions and processes

2.1 Definitions

Natural systems have been used as sources of inspiration for human designs throughout human history [Vincent et al. 2006] although the systematic use of biological knowledge in engineering design is relatively recent [Lenau et al. 2010]. Terms such as bionics, biomimetics, biognosis, bioinspired design or biologically inspired design were coined since the 1960s to characterize this process of using biological knowledge for improving or developing new technologies.
The first definition of biomimetics appeared in 1974 in the Webster's dictionary. It described 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]. A more general

definition, given by Shu et al. [2011] considers biologically inspired design and biomimetics as synonyms meaning "emulating natural models, systems and processes to solve human problems". The notion of emulation does not oblige that an identical copy of the biological inspiration is required as can be observed in examples such as the self-cleaning coatings inspired by the lotus leaves [Solga et al. 2007] or the Flectofin® inspired by the bird of paradise flower [Lienhard et al. 2011].
The reasons for searching inspiration in the natural world for design include the potential superior properties of natural phenomena compared to those of human-engineered technology, considering the former have been selected by evolutionary processes [Reed et al. 2009] and also the possibility of using the biological systems as analogies during the idea generation process [Smith 1998].
The number of publications in the biologically inspired field has grown exponentially since 1995, going from less than 200 publications (conferences and journals) per year to more than 2800 publications in 2011 [Lepora et al. 2013]. This growth has stimulated the attempts for methods aiming at systematically applying biological inspiration for technological improvement.

2.2 Directions for the biologically inspired design process: Solutions driven / problem driven

Using a descriptive account of the biologically inspired process during design classes [Helms et al. 2009] propose two approaches for the bioinspired design process: problem-driven and solution-driven. Other terms used in literature to refer to these two approaches are "top-down" or "technology pull" for the problem-driven and "bottom-up" or "biology push" for the solution-driven. The problem-driven approach starts by the definition of the problem to be solved using biological inspiration, followed by an abstraction of this problem in biological terms, in order to understand which would be the organisms, processes or characteristics of natural systems that could have interesting principles that could be applicable for solving the problem. Then the biological solution is abstracted and applied for solving the technical problem. The solution-driven approach starts with the identification of an interesting property in a biological system and a problem to which this property could bring a solution has to be identified.
These directions are similar to those of the Design Spiral or Design Lens, proposed by the Biomimicry 3.8 Institute [Biomimicry 3.8 2014]: "Challenge to biology", when there is a need for biological insights for solving a problem and "Biology to design", when a biological property inspires a new design.
Subsequent studies, reviewed on [Goel et al. 2014], describe the use of biological analogies in design process for: "solution generation, evaluation and explanation", identify that the biologically inspired design often uses multiple cross-domain analogies for composing the new design concept ("compound analogies"), and propose that conceptual design in biologically inspired design entails problem-solution coevolution.

2.3 Retrieving and transferring biological analogies

Tools for facilitating *the search and retrieval* of the biological analogues include the use of databases of biological phenomena such as the Asknature.org website [AskNature 2013] and consultations with biology experts, of natural-language written biology texts [Shu et al. 2011], of patents [Verhaegen et al. 2011], or of the internet [Vandevenne et al. 2012].
Computational tools are also being developed for facilitating the search and the analogical transfer process. DANE [Wiltgen et al. 2011] provides a knowledge base of biological systems, represented using SBF (Structure-Behaviour-Functions) models. IDEA-INSPIRE uses the SAPPhIRE model to describe the functioning of both technical and biological systems [Sartori et al. 2010].
Moreover, *Bio-TRIZ* is a theory developed for facilitating the transfer process between biology and engineering. By incorporating biological phenomena to TRIZ, using conflicts identified in a database of more than 500 biological phenomena [Vincent et al. 2006], biological principles can be compared to engineering ones and contribute for the final solution developed.

2.4 Research issue: the role of biological and traditional knowledge in the process

This brief theoretical background about the biologically inspired design process showed the progress made on the systematization and on the understanding of the process, using TRIZ, elaborating computational tools and databases or prescribing guidelines. The contents and the uses of the analogical transfer taking place during the biologically inspired design process were also evaluated in literature studies. Considering this background, we propose here to study the biologically inspired design process considering two general questions:

1. Why activating biological knowledge during the design process?
2. How does this process of biological inspiration take place?

Our hypothesis is that the biologically inspired design goes beyond the solutions finding or the analogical transfer between the biological knowledge and the traditional knowledge, described in literature. This means that the biological knowledge can trigger processes that act upon the two knowledge bases involved in the bio-inspired design: the biological knowledge base and the traditional knowledge base.

3. Methodology: Exploring biologically inspired design examples with the C-K theory framework

In order to explore the biologically inspiration design process, we selected three examples of biological inspired products and we modelled these examples using the C-K design theory framework (Figure 1). This theory allows a modelling of the generation of new objects which has a high level of generality [Hatchuel and Weil 2009], defining design as an interplay between two interdependent spaces, the space of concepts (C) and the space of knowledge (K). Space K contains the available knowledge, while space C contains propositions – the concepts – which are undecidable in K, i.e. they are neither true nor false about partially unknown objects. This interplay between the two spaces consists in an expansion of the initial concept into another concept, which corresponds to a partition of the concept, and/or into new knowledge. The design process ends when a design path, starting at the initial concept and ending at a partition of this concept, becomes a true proposition in K.

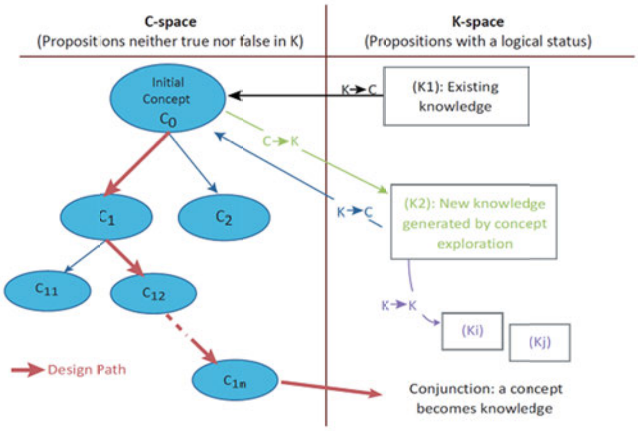

Figure 1. C-K diagram and operators (adapted from [Hatchuel and Weil 2009])

This double expansion of both spaces highlights the fact that design proceeds not only by generating solutions, but also by generating new concepts (that may not even be used in the final object, but that contributed for an expansion in the knowledge bases) and new knowledge, that can be useful for other purposes. The transformations between and inside spaces are called "*operators*". There are four operators in C-K theory: C→C, C→K, K→K and K→C. These operators create spaces with different structures. In C space only partitioning or inclusion are allowed, structuring it in a tree structure, in which each node represents a partition in several sub-concepts. Space K grows like "an archipelago", as new propositions are added without necessarily following a stable order or being directly connected [Hatchuel and Weil 2009].

4. Case studies

The three case studies we chose for analysing the bioinspiration process are: self-cleaning surfaces inspired by the Lotus plant [Barthlott and Neinhuis 1997], [Solga et al. 2007], a hingeless flapping mechanism (Flectofin®) inspired by the bird of paradise flower [Lienhard et al. 2011] and adhesives inspired by the gecko [Bhushan 2009]. The lotus and gecko inspired developments could be classified as belonging to a solution-driven approach, while the bird of paradise flower to a problem-driven approach, considering the two approaches proposed by Helms et al. [2009]. For all cases, a description of the case is given and is completed by the C-K modelling of the example.

4.1 Self-cleaning surfaces inspired by the lotus leaves

4.1.1 Case description

When studying the surfaces of leaves using scanning electron microscopy (SEM), Barthlott and Neinhuis [1997] observed that cleaning the leaves before examination in the microscope was not necessary for all plants. Plants with "smooth surfaces" always required cleaning, while those with "epicuticular wax crystals" were almost free of contamination. These crystals were already known by conferring water repellency and the link between particle deposition and surface roughness was already under study. However, the correlation between water repellency and reduced contamination was less straightforward and required more experimental data. Their experiments showed that the self-cleaning phenomena due to the correlation between surface roughness, water repellency and particle adhesion was very strong in the Lotus (*Nelumbo nucifera*) leaves. The observations made on these surfaces led these scientists to propose a model that explains the observed self-cleaning phenomena. They used knowledge from the behaviour of liquids applied on solid surfaces considering the wettability and roughness of the surfaces. This knowledge was already in the traditional knowledge bases, but the lotus leaves showed one way of producing the self-cleaning effect. Solga et al. [2007] affirm that the idea of obtaining self-cleaning properties with surface changes was not immediate before the Lotus plant observation, and that a study that aimed at first at a taxonomic classification of plants surfaces produced these surprising results.

4.1.2 C-K modelling

This case development is schematised using a C-K framework (Figure 2). The research activities of Barthlott and Neinhuis represent an expansion of the biological knowledge bases about leaves structures. These activities led the researchers to the identification of an unexpected property considering the self-cleaning surfaces: rough surfaces had self-cleaning properties whether smooth surfaces did not. This represents a partition of the concept of "designing self-cleaning surfaces", the other partition being self-cleaning surfaces with smooth surfaces.

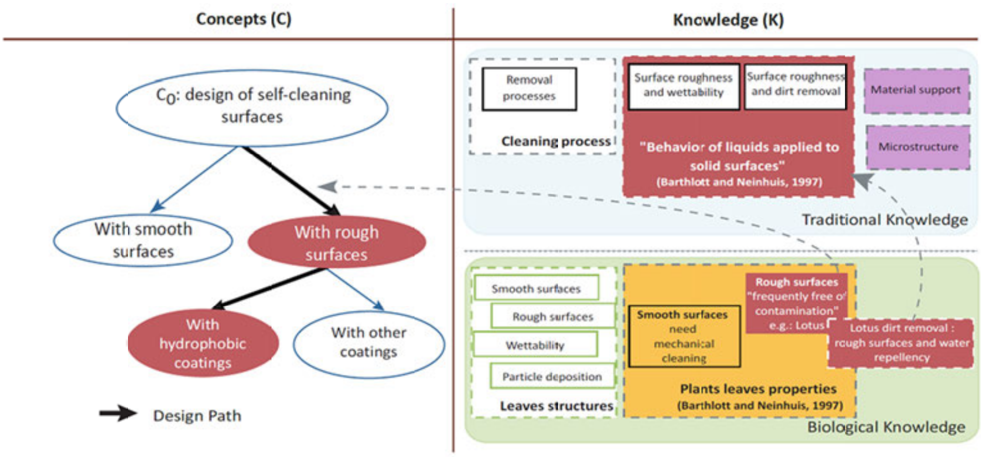

Figure 2. C-K diagram for self-cleaning surfaces inspired by lotus leaves

Moreover, they also observed that the roughness was related to the epicuticular crystals that had a hydrophobic coating. For describing this relation between hydrophobicity and roughness, the traditional knowledge bases for explaining the behaviour of liquids applied on solid surfaces were necessary. This return to the traditional knowledge bases is an expansion of the knowledge used for the design process. Once these scientists understood the relationship between hydrophobicity and surface geometry, they developed prototypes for this system not using the same structure or coatings as the Lotus, but rather human-made ones which had similar properties [Solga et al. 2007], which represents a traditional knowledge based development.

4.2 Hingeless flapping mechanism inspired by the bird of paradise flower

4.2.1 Case description

In architecture, the use of technical hinges for deployability, in blinds and umbrellas for façade shading for example, is considered as an issue because these pieces have constant load cycles that wear the mechanical pieces and induce the need for constant maintenance [Lienhard et al. 2011]. While these hinges are necessary in architecture, some plants show that hinge-free movements and reversible deformation mechanisms. This observation was the starting point for 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. During this collaboration, a screening process on plants movements led to the identification of a suitable kinematic principle for a façade shading system that did not use hinges and rollers.
This principle was identified during the screening process, when engineers and architects were building physical models that reproduced the deployable and reversible systems they observed in plants. The mechanism responsible for the opening and closing movements of the two adnate petals on the bird of paradise perch, which is activated by pollinating birds landing on this perch, was understood as a special form of lateral torsional buckling. Although not completely unknown to these architects and engineers, buckling is normally perceived as a failure mode of materials. The researchers have then proposed a physical model of the flower opening mechanism and the final system was prototyped and patented, as a shading mechanism for façades, with the name of Flectofin® after the characteristics of the materials and structural behaviour were defined.

4.2.2 C-K modelling

In this case (Figure 3), the question of finding a new way for producing a more adaptable deployable system, triggered the activation of biological knowledge about deployability in Nature. The observation of this knowledge base showed that deployability without hinges was possible. This partitions the initial concept, as deployable systems not using hinges did not belong to the designer's knowledge bases.

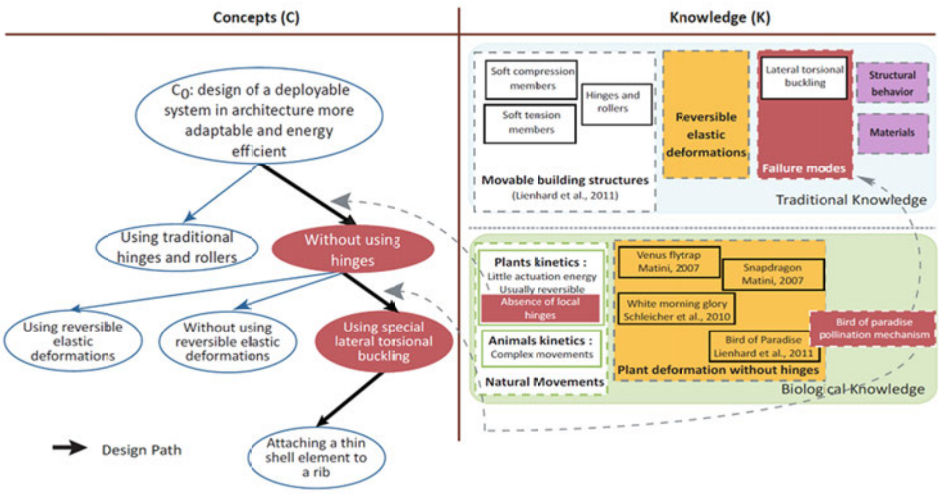

Figure 3. C-K diagram for hingeless flapping devices inspired by the bird of paradise flower

Developing the concept of "deployable systems without hinges" required further investigation on plants movements, which represent an expansion of the biological knowledge and this investigation also led to an activation of the traditional knowledge on materials deformation, in order to explain the observed movements of plants. When the bird-of-paradise pollination mechanism was identified, a non-spontaneously activated knowledge base (lateral torsional buckling) was activated (buckling was normally considered as a failure mode) and formed a concept, as the flower buckling did not exactly correspond to the existing phenomena of buckling, which belongs to the traditional knowledge bases. The next steps of development included the use of "traditional knowledge" in order to see how this model could be built, which was obtained by attaching a thin shell element to a rib and also by studying the possible applications of this property in architecture. The final design path led to Flectofin®, a shading mechanism for façades.

4.3 Gecko-inspired adhesives

4.3.1 Case description

Gecko's outstanding adhesive properties in practically any kind of surface have inspired scientists to understand this process and also to apply this knowledge on designing new reversible adhesives [Boesel et al. 2010]. The mechanisms of gecko's adhesion seemed different from the traditional wet adhesion used by the most common man-made adhesives [Bhushan 2009]. These differences stimulated researches to explain the adhesion properties observed in geckos. Some hypothesis included suction, friction or intermolecular forces [Autumn et al. 2000]. These authors demonstrated that the intermolecular forces, more specifically the van der Waals forces between the setae (keratinous hairs covering gecko's toes) and the surface were responsible for the attachment properties. They have also observed that the movements of the gecko's toe also contributed to the adhesion properties of setae. The knowledge about the gecko's adhesion properties and the comprehension of its adhesion phenomena due to the fibrillar hairs of the toe pads stimulated the research on materials with nano- and micro-structured fibrillar surfaces that would have dry adhesion properties [Bhushan 2009]. Observing that these materials had poor adhesive properties at larger length scales, Bartlett et al. [2012] used the knowledge about gecko's adhesion and developed a scaling theory which allowed the creation of adhesives with unmatched adhesive properties, even without fibrillar structures.

4.3.2 C-K modelling

For this case, schematised on Figure 4, the initial knowledge about gecko's movements (reversible and strong adhesion properties) represents the initial biological knowledge base. These properties also activated the traditional knowledge bases on adhesion phenomena, as researchers searched in their knowledge bases for explanations on the observed properties. The properties of geckos were unmatched by human adhesives. Therefore, designing surfaces with strong and controllable adhesive properties was the initial concept.

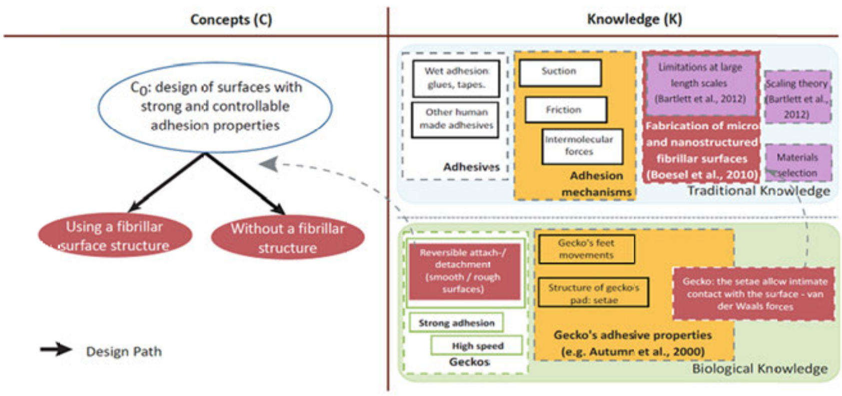

Figure 4. C-K diagram for gecko-inspired adhesives

Further studies on the gecko's properties were required for understanding why these properties were observed, which in C-K are represented by expansions on the biological knowledge bases. The identification of the gecko's fibrillar structure of setae as the mechanism responsible for adhesion represented an unexpected property considering the traditional knowledge. This unexpected property thus can be considered a concept, "using a fibrillar surface structure", that partitions the initial concept. The manufacturing process was pursued using traditional knowledge about materials properties and characteristics for producing fibrillar structures. The observations on the scalability of these adhesives, led to a revision of the traditional knowledge about adhesion with the fibrillar structures, showing that this structure was not a necessary condition. This also partitions the initial concept: achieving the same properties without the fibrillar structure.

5. Main findings: A model for biologically inspired design

When comparing the biological inspiration process of the three case examples modelled using the C-K theory framework (Table 1) we observe that in the three cases, the initial biological knowledge bases activated had an unexpected property, i.e., a property that could not be explained using the traditional knowledge available to the designers. This unexpected property has two effects: (i) a stimulation in the concepts space, which generates a partition of an initial concept which could not easily be partitioned only using the existing knowledge available to designers, and (ii) a stimulation in the knowledge space, by expanding the biological knowledge bases on the unexpected property (with a screening process searching for other systems that could have the same property) and also expanding the traditional knowledge bases. This expansion is the activation of traditional knowledge for explaining the properties observed in the biological knowledge.

Table 1. Results observed using the C-K framework for the three examples

Case	First "unexpected property" in Bio-K	Role of this "unexpected property"	Other unexpected property in Bio-K	Role of this "unexpected property"
Self-cleaning surfaces (Lotus leaf)	Rough surfaces frequently free of contamination	C-partitioning Bio & Traditional-K expansion	Lotus leaves self-cleaning properties	C-partitioning Traditional-K expansion
Flectofin® (Bird of paradise)	Plants movements without technical hinges	C-partitioning Bio & Traditional-K expansion	Bird of paradise pollination mechanism	C-partitioning Traditional-K expansion
Controllable adhesion (Gecko)	Reversible attachment	C-partitioning Bio & Traditional-K expansion	Fibrillar structures in geckos feet	Traditional-K expansion and revision

Table 1 also indicates that after the identification of this first unexpected property, the expansions on biological knowledge led to the identification of another unexpected property. This property partitions the concepts space, by adding a new property to the initial concept, and expands the traditional knowledge bases, without requiring further expansions on biological knowledge. For example, in the lotus case, once the lotus cleaning mechanism was understood, the next steps included product development using this property but built using traditional knowledge bases expansions.

These results highlight the main reason for seeking inspiration in nature for design: finding alternative design paths for design paths elaborated only using the traditional knowledge bases and expansions. These design paths may seem "blocked" as the alternatives generated using only the traditional knowledge are not sufficient for the designers. Another important outcome of this modelling process is a possible explanation for the differences observed between the biologically inspired products and their sources of inspiration, as the unexpected property found in the biological knowledge is not used as it is observed in the natural system, it triggers concepts partitioning and its development will depend on the traditional knowledge bases it activates.

Using these observations from the three examples, we propose a model with four steps for the biological inspiration process using the C-K design theory framework, schematized in Figure 5.

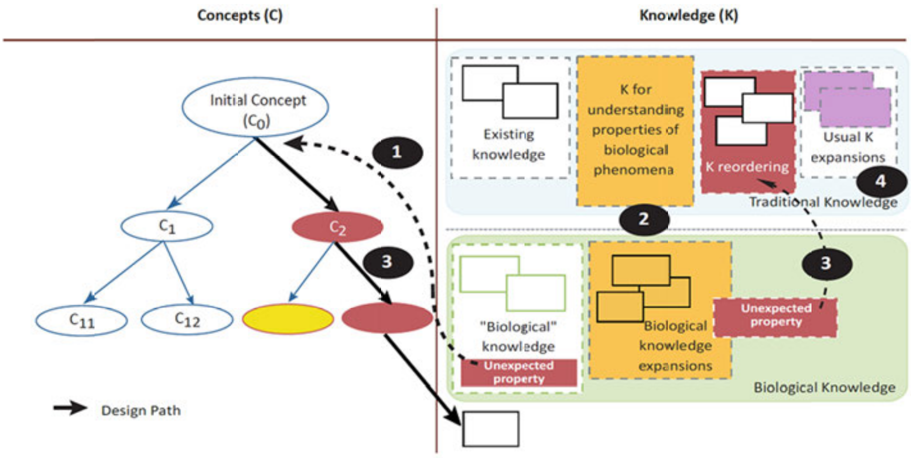

Figure 5. C-K framework representing the main steps of the biological inspiration model

Step 1: Activation of biological knowledge

The search for knowledge bases which are different from the traditional knowledge bases available to designers is stimulated by some blockage of the traditional design paths. This blockage refers to a difficulty in partitioning a concept. In the lotus case, this blockage referred to the traditional consideration that "things do not clean themselves" [Solga et al. 2007], for the Flectofin® case the fact deployability was generally achieved using hinges and rollers, and for the gecko adhesives, the common man-made adhesives used wet adhesion (glues, liquids) [Bhushan 2009]. The activation of biological knowledge, on leaves surfaces (Lotus), on plants movements (Flectofin®) and on geckos' adhesive properties, led to a partition of a concept, by adding a property coming from the biological knowledge, which was unexpected considering the traditional knowledge available to these designers.

Step 2: Expansion in biological and traditional knowledge

After partitioning a concept with an unexpected property from the biological knowledge, this new concept will trigger two expansions: an expansion in the biological knowledge base, for evaluating whether the observed property is found in different examples. This was illustrated by the analysis of different leaves that were or not free of contamination in the Lotus case, by the screening process on different plant deformation mechanisms in the Flectofin® case and by evaluating the structure and movements of Geckos at the Gecko's case. This biological knowledge expansion also involves a traditional knowledge expansion, as the researchers were looking for explanations about the phenomena they were observing.

Step 3: Exploration of the traditional knowledge and concepts partitioning

A property in the biological knowledge base can be considered as unexpected when the traditional knowledge bases available to designers are not sufficient for completely defining this property, as previously explained. According to our observations on the three case examples, an unexpected property has two roles: triggering an exploration of the traditional knowledge, as designers will have to expand their knowledge to find some knowledge bases that would help them understanding the property, and partitioning the concept that was previously guiding the biological knowledge, by adding a new property to this concept. The same process occurs in step 1, although the unexpected property of this third step partitions the concept but do not require further biological knowledge expansions as the traditional knowledge reorganization made further product development possible. In the Flectofin® case, during the screening process of different plant movements, architects and engineers activated knowledge on reversible elastic deformations for explaining the phenomena they were observing in nature, but the Bird of Paradise flower represented an unexpected property considering that the phenomena behind the flower opening and closing movements was the lateral torsional buckling, which was not a knowledge spontaneously activated by these designers, as buckling is usually considered as a materials failure mode to be avoided when building architectural systems.

Step 4: Return to the traditional knowledge bases

In the three case examples, once the unexpected properties of biological knowledge bases were identified, and the traditional knowledge bases reorganized, the design process described for achieving the final design (the self-cleaning paints, the Flectofin® system, the gecko's adhesives) mostly used the traditional design considerations, and did not require expansions of biological knowledge about the unexpected property. This could explain the differences between the initial biological source of inspiration and the final design produced. The lotus leaves have rough surfaces, while the Lotus-inspired product is a paint that produced the required roughness in the surface. The Flectofin® system is used for façade shading and do not have pollination functions. Finally, for the gecko, the microfibrillar structures were built using other materials and the work of [Bartlett et al. 2012] based on the geckos adhesion showed that similar adhesive properties could be obtained even without using fibrillar features.

6. Conclusions and further work

6.1 C-K modelling for biologically inspired design

This modelling of the bio-inspired design with the C-K design theory highlights three main aspects of this process:

- *Biologically inspired design goes beyond analogies or inspiration during idea generation:*

Using biological knowledge during the design process also implies an expansion on both knowledge bases, the traditional and biological. This expansion allows the identification of unexpected properties. These properties partition or create a concept, as they cannot be defined using the knowledge bases available to designers. They also guide the exploration of both knowledge bases. Consequently, the biological knowledge does not automatically produce "solutions": It stimulates concept partitioning and knowledge exploration in both knowledge bases, biological and traditional.

- *Biologically inspired design triggers organisational changes:*

The expansion of both knowledge bases requires a dialogue that could be defined as "mutually inspirational" as the properties identified in one base will guide the exploration of the other. Consequently, researches in both fields will have to be organized in parallel, and their interaction will guide the knowledge exploration and the definition of new research directions.

- *The C-K framework facilitates the exchanges in biologically inspired design:*

The C-K representation shows the knowledge bases and the interactions triggered by their expansion and the formulation of concepts, which can be useful during the design process, facilitating the "encounters" between biological and traditional knowledge. However, the framework does not explain how to find "suitable" biological knowledge bases. This could be achieved using the methods for finding and retrieving biological systems, such as the computational tools, databases, natural-language or functional representations.

6.2 Further work: An industrial application and comparisons with other creative processes

The results of this model and the C-K framework are being applied on an ongoing research project in a large automaker company aiming at formulating concepts for energy management in vehicles, using biological knowledge on animal energy systems. Further work should elaborate the C-K model for biological inspiration using these field observations, and relate these observations to existing design methods already used for innovation in this company. Another direction being pursued is the comparison of these results with other creative process, for example, the ones encompassing interactions between knowledge bases involving similar domains with different characteristics, which were captured by the Infused Design method [Shai et al. 2013].

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