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BIO-INSPIRED DESIGN CHARACTERISATION AND ITS LINKS WITH PROBLEM SOLVING TOOLS

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1. Introduction

Design activities have a significant influence on human health and quality of life. It requires a certain knowledge to perform a design process. This knowledge may come from various sources such as people designers, experts, etc.), products or processes, and can be different in its nature [Hatchuel and Weil 2003], making their aggregation more difficult to designers. Those bits of knowledge and their wider scope of points of origin lighten the current dissolving of the scientific disciplines, combined with the development of highly specialized domains [Kostoff 2008], [Schöfer et al. 2013].
The efficteveness of use of biology knowledge, often combined with other scientific disciplines, as source of innovation, has been demonstrated throughout history of mankind [Simon 1983]. In early times, human beings observed animals and mimicked their hunting, shelter and survival behaviors. In Renaissance times, Leonardo da Vinci already tried to mechanically understand how birds fly to design his first flying machine. Bio-inspired design enjoyed a new boom in the 50's thanks to aerospace, marine and automotive industry and, to a minor extent, cybernetics and complex system modelling. During the 80's bio-inspired design has grown on micro and macroscopic levels in the light of biotechnology [Schmitt 1960], [Steele 1960], [Gleich et al. 2010], [Bar-Cohen 2011]. Keeping these facts in mind, the transfer of principles from world of living organisms towards technology is, therefore, by no means a new phenomenon. However, streamlining the approach, defining bio-inspiration as a scientific discipline, a method, or a philosophy crystallises the novelty. Bio-inspiration, as a contemporary concept, defines itself as an attempt to develop innovations by combining biology and technology. Its theoretical base takes advantage of the optimisation of biological structures, functions, processes and systems by successive evolutions which characterises living organisms.
The article will firstly raise issues upon definitions and conceptual boundaries of the terms related with the bio-inspired design. After the presentation of biomimetics case studies, the focus of the article, driven on a theorical level, will be set on the generation of a generic problem driven biomimetic process. The tools and methods than BID can reap advantage from will therefore be addressed.

2. State of the art of semantics

Bio-inspiration is a domain with a proliferation of terms. It is therefore interesting to take a closer look at them. The first term to appear in modern literature is "biomimetic" which according to the Oxford English Dictionary is indexed in the volume 132 of Science, published in December 1960. The index refers to two published articles, defining the term as devices which simulate biological functions. It is also in 1960 that the term "bionics" is used for the first time, in a scientific article [Steele 1960], without being explicitly defined. Still in 1960 the Merridian Webster Dictionary defines bionics as a "a science concerned in the application of data about the functioning of biological systems to the solution of engineering problems". Biomimicry emerged much later, in 1997 [Benyus, 1997] as the eco-design part of bio-inspiration. It emphazises the resilient aspect of provided solutions. Combining the prefix bio-, from greek "bio" meaning life, and the suffix mimesis from the greek "mimeisthai" meaning imitate. By its use from environmental lobbies, the biomimicry term enjoyed a strong position, especially in the United-States, where it has its origins, and it is now the most commonly used term among bio-inspiration.

Reading all these definitions consecutively brings their lack of clarity to evidence. That lack of well defined boundaries between terms leads to redundancy of concepts and confusion of goals and aims. Nowadays, as acknowledged by Vincent et al. [2006], biomimetics tends to become a synonym of biomimicry, biomimesis or even biognosis, whereas they are all equivalent to bio-inspiration. This situation leads to an inappropriate use of terms and contributes to "green washing" in this emergent field.

A cross analysis of the literature, partially carried out within a standardization committee, leads us to propose the following new definitions:

Biomimetics: Interdisciplinary creative process between biology and technology, aiming at solving antrophospheric problems through abstraction, transfer and application of knowledge from biological models.

Biomimicry/Biomimesis: philosophy that takes-up challenges related to resilience (social, environmental and economic ones), by being inspired from living organisms, particularly on an organizational level.

Bionics: technical discipline that seeks to replicate, increase or replace biological functions by their electronic and/or mechanical equivalents.

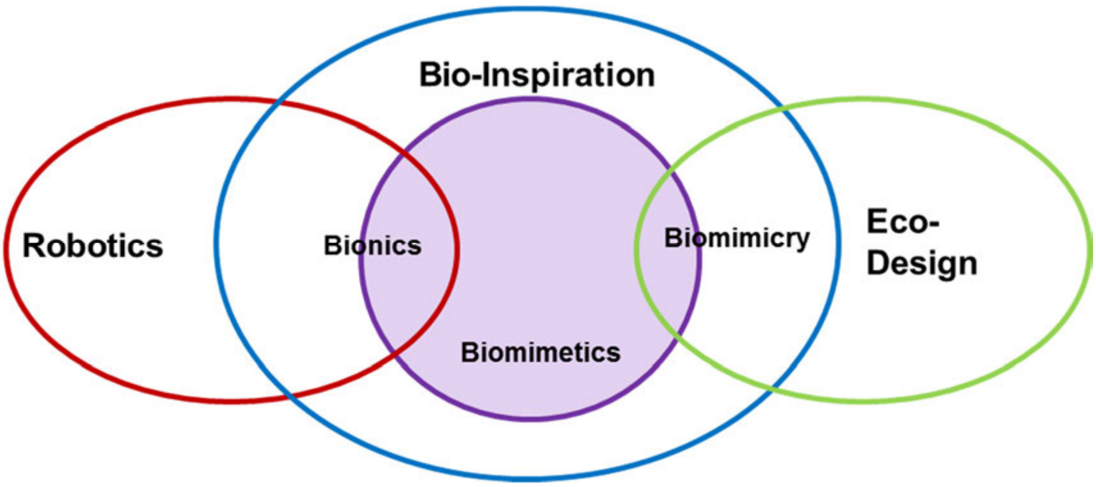

Figure 1. Bio-inspiration and linked concepts boundaries map

These new definitions, in a more precise way, define the conceptual boundaries of each term, as shown in Figure 1. However, they do not allow to overcome interpretation issues, even if they are reducing them, with the areas in which they apply.

3. Biomimetic cases studies analysis

Theorised by Janine Benyus [1997], bio-inspiration could be achieved according to three levels. The first one comes down to mimicking form. The second level overcomes form to reach the mimicking of natural proceses, where focus is set on mimicking structures and functions. The third and last level concerns mimicking the strategies of the living. Its goal is to reproduce the relationships of a mature ecosystem in constant interaction and dynamic homeostasis with its environments.

In this section 3, biomimetics case studies, considered as classics in BID literature, will be presented according to their level of inspiration and their methodological output analysed.

3.1 Inspiration of form: Shinkansen

The Shinkansen, also called the Japanese bullet train is the fastest railway train in the world, travelling at more than 300 km per hour through urban areas. Sudden changes of air pressure combined with its high speed cause a thunder clap every time the train emerges from a tunnel. That noise and the proximity of the railway lines to residential areas was a significant issue. Eiji Nakatsu, Director of theTechnical Development and Test Operation Department of JR-West, was in charge of dealing with this noise situation. Infatuated with ornithology, he drew inspiration from the sharp and longilineal shape of the Kingfisher's head, able to glide through the air and precisely dive into water to snag fish with no splash. The fundamental problem is the same in both world, to make the transition from a low pressure environment which is air for the Kingfiher, to high pressure environment which is water for the Kingfisher. Several other inspirations from living organisms were used trying to improve the Shinkansen's impact on surrounding homes. The first one was serrations from Owl's primary feathers as source of inspiration to limit vibrations of the pantograph. The second one was the spindle shape like the one of the body of the Adelie Penguin, used to reduce the degree of wind resistance of the supporting frame of the pantograph.

By combining all these different inspirations of forms from living organisms, the West Japan Railway Company reduced the energy consumption of the train by 15%, while travelling 10% faster within existing acoustic standards.

This example shows that when the required technical expertise and biological knowledge are concentrated in a single person, the biomimetic process does not seem more complex than a classic design process.

3.2 Inspiration of process: Gecko tape [Geim et al. 2003]

That adhesive tape is a material with synthethic nanotubes mimicking the tiny hairs known as setae of the gecko's foot. In nature, flexible filaments packed at 5,000 per mm2 create Van-der-Waals bonds that cause a powerful adhesion effect. Expected applications range from undersea to spatial environments.

Following the first attempt, scientists became aware of the significant need of energy to detach their band from the surface. After several usage cycles, tensions exerted on the nanotubes were so high that the tape wasn't able to fulfill its function anymore.The geckno twists its setae when moving, creating angle and variation in their relative distance, reducing Van-der-Waals forces. With this process, the gecko is able to run without its adhesion mechanism becoming a constraint. Researchers response to this issue was to replace polyamide filaments with more resistant polypropene ones. The need of clean surfaces is another phenomenon that has only been identified following the completion of the study. The tape tends to rapidly loose its adhesive capacity by amassing dust particles. In the living world, the gecko keeps its "adhering surface" in operating condition by continually licking its paws combined with self-cleaning capacity. Scientists have not been able to take up this technological challenge for a long time.

Regardless of the scientific success of this study, the gecko tape case shows that in order to lead to an industrial success, a biomimetic process must take into account every surrounding element of the desired function. Otherwise efficiency of concepts developed could be seriously affected or even null, unable to be transformed into technological successes.

3.3 Inspiration of system: Eastgate Centre [Turner and Soar 2008]

The Eastgate Centre in Harare, Zimbabwe, was built in 1996, following several years of study of termite mounds, lead by the architect Mick Pearce and the scientist Scott Turner. Termite mounds have the fascinating ability to maintain In a passive way a specific temperature, 31°C ± 1°C, with ambient temperatures ranged from 3°C to 42°C. Insects achieve this prowess thanks to the thermal capacity of the mound material combined with fungal-based cooling vents, managing a carefully adjusted convection current system throughout the structure.

The passive ventilation system of the Harare Eastgate Centre wasn't a success, temperature could not be kept steady. Installation of low-speed fans on the first floor of the building resulted in tremendous improvements. Due to its design, the Eastgae Centre claims a consumption of 10% of a standard building of a similar size.

Theorically the project failed; design did not succeed in passively controlling the tempature. Practically the project succedded, owners of the building saved almost 3.5 billions of dollars by not installing a standard ventilation system, inhabitants rent their accommodation 20% less than inhabitants of the surrounding buildings. Impaired version of living systems could therefore still lead to impactfull innovations without matching the ideality of its model(s) of inspiration.

These few examples coupled with other ones described in literature allow us to draw some general conclusions. Biomimetics doesn't necessarily imply sustainability. For example, superhydrophobic coatings based on the lotus effect are still produced from the distillation of petroleum. Some biomimetic solutions even lead to new technical or ethical difficulties. Spider silk fiber synthesis that may involve transgenic mammals illustrates this fact.

Some solutions, without breaching their relevance or efficiency, presented as biomimetic are not legitimate. Energy production from articifial seaweed belongs to bio-inspiration/bio-assistance but not to biomimetics. Products developed thanks to evolutionary algorithms also do not fit the biomimetics requirement mentioned in the proposed definitions as they are not inspired from a identified biological model. Presented solutions for commercial purposes such as current biomimetic cosmetics, as they do not offer any transfer step, are another typical example of mislabelled biomimetic products.

As a consequence, the definitions presented in section 2 make it easier to determine if debatable cases are biomimetic or not.

In the search for innovative solutions, biomimetics act as a supplement to the classic methods for developing new ideas, as a way of approaching scientific engineering work methods. Living organisms and their amazing adaptations offer a virtually infinite number of potentially relevant solutions from a technological point of view.

4. Characterisation of a generic biomimetic method

As seen in section 3, what distinguishes bio-inspired real success cases from others seems entwined with the logical process adopted during design phases. Thus, it is this design strategy that distinguishes bio-inspired accidents from biomimetic products. It seems thus important, not to let aside biomimetic methodological aspects when tackling bio-inspiration as a pratical research field of interest.

The number of scientific researchers and industrial practitioners related to bio-inspiration is growing but transferring knowledge from biology to technology is still a complex process. Methodogy as a starting point could lead to improvement in simplyfing such approach.

It is then interesting to draw a correlation between this kind of approach and methods and tools from the "classical" literature of design in order to identify means biomimetics can reap advantages of. Several design tools and methods exist, Lahonde categorized them into different families [Lahonde 2010]. Regarding Table 1 and the purpose of these different clusters, biomimetics coincides largely with creative methods. Given that creativity tools and methods tend in their purpose to solve a problem, every aspect of a biomimetic approach could be put in perspective with problem solving theories, methods and/or tools, which are by far described in more detail within literature of design.

Table 1. Extract of design methods clusters (translated from [Lahonde 2010])

Cluster	Aim	Profession	Examples of methods
Market	Match client expectations	Marketer	Survey/Opinions polls
Specifications	Translate the client's and users' need in technical language	Engineer	Internal and external functional analysis
Creativity	Innovate, differenciate from competitors Find creative solutions	Various	Brainstorming Morphological box
Safety	Fulfill functions in set operating conditions, managing risks	Engineer	FMEA
Environnement	Consider environmental impact	Engineer	Life cycle assessment

4.1. Steps of a classical problem solving

Problem solving is a cross disciplinary concept. Its terminologies and perspectives may differ from the domain in which it is applied, for instance, it is a mental process in psychology but a computerized process in computer science. Either way, problem solving can be described as a logical process that consists in both sense-making and action-taking. Using a phase or stage description, the problem solving process consists in a 5 steps process [Massey and Wallace 1996]:

1. Identification: process by which a model is developed by assembling components and relationships from the stimuli that led to the recognition and identification of the problem.
2. Definition: Process by which the problem is analysed in order to identify the possible causes, the root causes or the main causes.
3. Alternative generation: Creative process by which unique solutions or groups of solutions are generated attempting to solve identified causes.
4. Choice of a solution between ideas generated to solve the inital problem.
5. Implementation and testing: Implement the choice of a solution in the initial problem and resolve issues and challenges underlying. Evaluate the final solution, ensure results achieved and disseminate related information.

4.2 Steps of a generic biomimetic method

Biomimetic could be used with two separated ways, solution driven method or problem driven method. The solution driven method assumes a biological system that performs a function that the engineer wants to emulate as a starting point. The process is focused on abstracting the biological system so that the designer can then use the functional model to inspire an engineering design concept. The problem driven method assumes that there is a specific behaviour/function that the designer wishes to perform. The process is focused on determining the biological systems that need to be considered for inspiration. The rest of the article will focus now on on the problem driven (PD) method of biomimetics.

The bioinspired problem driven process has already been described within literature. Bogatyrev and Vincent outline a 6-step process which focuses on extracting essential features from biological models in order to translate them into technological knowledge [Bogatyrev and Vincent 2008]. Helms et al. define a 6 step problem-driven biologically inspired design process [2009] which provides iterative feedback and refinement loops. This process has been adapted by Vattam et al. to develop the DANE approach [2011]. Nagel et al. proposed a 7-step process which starts from the identification of the biological system of reference, and focuses on the functional establishment of a pattern/model of biological models [Nagel et al. 2010].

By analysing examples among the bio-inspiration literature from the prism of a cross analysis of the problem- driven above-mentioned processes with regard to the definitions outlined in section 2.2, a new logical pattern can be established. This pattern is articulated around 9 different steps:

1. Define the human needs/challenge.
2. Abstract the technical problem by selecting appropriate functions and constraints.
3. Translate the abstracted technical problem into a biological challenge.
4. Identify potential biological models that solve the translated abstract problem.
5. Select the biological model of interest amongst potential candidates.
6. Abstract biological strategies from the selected biological model in order to reduce the number of constraints.
7. Translate these identified biological strategies into a technological challenge.
8. Resolve issues related to solving the technical challenge of implementing the final solution to the initial situation.
9. Evaluate the final solution, ensure results achieved match the initial expectations, initiate steps related to improving the generated design.

Refering to the work of Massey and Wallace, the problem driven biomimetic process could be schematised as follows:

Table 2. Problem driven biomimetic process in regards of solving problem process

1. Identification	2. Definition		3. Alternative generation	4. Choice of a solution	5. Implementation and testing			
1. Define the human needs/challenge	2. Abstract the technical problem	3. Translate into a biological challenge	4. Identify potential biological models	5. Select the biological model of interest	6. Abstract biological strategie(s)	7. Translate into a technologica l challenge	8. Implement to the initial situation	9. Evaluate

Structured that way, designers are more willingly to understand what is involved in a biomimetic process. Biologists who experienced bio-inspired design, or intend to, could also correlate the approach with a classical problem solving process, and its description in literature.

4.3 Link with inventive methods

Having identified the generic steps, it appears that a link exists between biomimetics and inventive methods and more specifically with TRIZ.

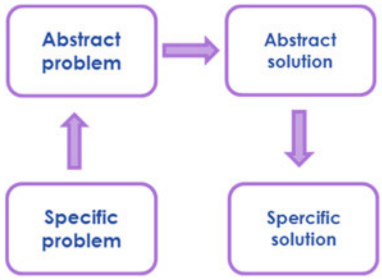

Figure 2. TRIZ process for creative problem solving

The Figure 3 presents the classical triz process, illustrated in Figure 2, applied to the generic problem driven biomimetic process.

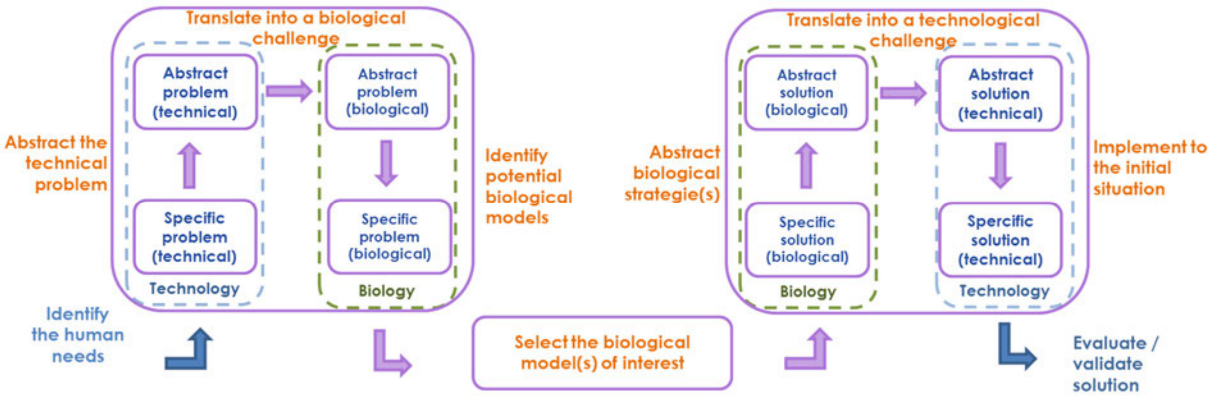

Figure 3. Link between TRIZ and biomimetics

The outline of the problem driven biomimetic process appears as a double TRIZ cycle, which corroborates Vandevenne's proposed SBID approach [Vandevenne et al. 2013]. The left part of the figure, the first cycle, focuses on a technology to biology process while the right part of the figure tackles its way back, from biology to technology.

Between these two parts of the figure lays a pivotal step, the selection of the biological model(s) of interest. This step seems crucial as it stands as a support for the whole biology to technology approach. A lack of equivalence between technogical and biological constraints when it comes to chosing a model of inspiration would more likely lead to unefficient final solutions.

Looking at the major steps of the process, the global cycles suggest that making technologists and biologists work together, the ones after the others with a translation steps between their output might appear as the right process. With a closer look, the figure emphasises the intertwining aspect of both cycles. Each cycle requires knowledge coming from both worlds in its sequence implying technologists and biologists not only to work the ones after the others but to cooperate. That need of synergy between biology and technology represents the difficulty in the background of any bio-inspired process. The current response aims at reducing the need of involved interdiscinirarity instead of facilitating it. For that purpose, tools such as databases are developed. These databases focus on gathering and formalising biological knowledge in a way they can be accessible to technicians.

5. TRIZ tools potential use regarding the problem driven biomimetic process

Biomimetics offers a unique possibility, the ability to provide methods, guidelines and tools that could rely on more than 3.8 billion years history of challenge solving thanks to natural selection. In many fields, living organisms outperform man-made solutions by far and biomimetic solutions are thus widely regarded as not only being ingenious, but also being ecologically sound, and resilient. Biomimetics are not, however, free of weaknesses. Constraints regarding interdisciplinarity in making technical engineers work with biologic material and biologists, and vice-versa, as mentioned in section 4, are not easy tasks. Similarly, the inherent need, with intervals of various depth, of fundamental research in particular during the step of biological strategie(s) abtraction, tend to lengthen the design cycles compared to non biomimetics ones. Thus, it seems interesting to identify from which tools and design approaches biomimetics could benefit in order to compensate the weaknesses mentioned above. With its link to TRIZ, it is now interesting to figure out which TRIZ based tool could be used theorically at each step in order to fulfill its purpose. Based on Schöfer's work [Schöfer et al. 2013] which emphasises Savransky's [2002] and Nakagawa's [Nakagawa et al. 2003] previous work, we propose in Table 2 a mapping of TRIZ tools regarding the problem driven biomimetic generic process steps.

Table 3. Match between TRIZ tools and generic problem driven biomimetic process

	Identification	Definition		Alternative generation	Choice of a solution	Implementation and testing			
	Define the human needs	Abstract the technical problem	Translate into a biological challenge	Identify potential biological models	Select the biological model of interest	Abstract biological strategie(s)	Translate into a technological challenge	Implement to the initial situation	Evaluate
Ideality (IFR)	x	x				x			
Su-Field Analysis		x				x			
9 windows	x								
Identification of resources		x	x			x	x		
Technical Contradictions		x				x			
Inventive Principles			x				x		
S-Curve Analysis	x								
Physical Contradictions		x				x			
Smart Little People		x				x			
Inventive Standards			x				x		
Brainstorming			x				x		

The theory of inventive problem solving seems to offer, cf. Table 3, a wealth of tools which might be capable of addressing the specific needs outlined. Tools coming from TRIZ tackle entirely the identification and the definition of problem solving steps. The implementing and testing phase is only partially addressed. Tools ogirinating from TRIZ only focus the first half of the mentioned phase.

TRIZ listed tools do not seems to offer tools focusing on "alternative generation" or even "choice of solution" which was define as a critical step in section 4.3.

6. Relevance of TRIZ tools for BID methods?

The choise of tools, according to the process, has been outlined but nothing allows biomimetic designers to choose which tool or set of tools to use regarding their relevance to the task. For this purpose, we need to compare tools. It makes no sense to compare tools with different objectives, thus an appropriate classification has been achieved. Definitions in section 2, indicate that every biomimetic approach implies abstraction, transfer and application. Therefore, an attribute, "abstraction", "transfer" or "application is assigned to each step of the biomimetic process according to its main output step goal. To match BID literature, another attribute has been added to the ones mentioned in the definition. This attribute, "evaluate", classifies tools that analyses the global/whole process and allows designers to initiate counter-measures or even to loop to another cycle.
Results are shown in Table 4:

Table 4. Steps of a generic biomimetic method and their classification

Identification	Definition		Alternative generation	Choice of a solution	Implementation and testing			
Define the human needs/challenge	Abstract the technical problem	Translate into a biological challenge	Identify potential biological models	Select the biological model of interest	Abstract biological strategie(s)	Translate into a technological challenge	Implement to the initial situation	Evaluate
Abstract	Abstract	Transfer	Application	Application	Abstract	Transfer	Application	Evaluate

It is noticeable that the first abstraction step, the one that occurs in the technical field, includes two distinct sub-steps, one which deals with identification aspects and the other involving abstraction. The abstraction step intervening in the biological field involves exclusively abstraction. Sub-targets and means involved to achieve these steps differ, even if concerned parties share the same overall objective.
With these different classes of tools identified, comparing tools from the same category is now possible. A list of criteria has been established in order to do so.
The list of TRIZ tools shown in Table 3 does not offer "application" or "evaluate" tools, therefore the reminder of the article will focus on "asbstracting" and "transfering" tools.

6.1 Abstracting tools

Abstracting tools, as mentioned before, due to the first abstraction step, the biological one, pursued two different objectives: problem identification and problem modelling. To fulfill those objectives from the theoretical contribution point of view an ideal abstracting tool should

- Be able to model complex problems in order to fit as much cases as possible;
- Strongly integrate different systemic levels to allow designers to model their problems precisely;
- Effectively filter information regarding its significance for the problem solving process, to avoid overflowing designers with information they do not need;
- Establish a very strong access to the problem in a generic way in order to allow its translation into a biological challenge;
- Completely maintain specific constraints with respect to the generated generic problem by avoiding an over generification of the problem which could lead to identification of biological models that do not solve the original technical problem.

From the practical/operational point of view, an ideal abstracting tool

- Should be able to be implemented with very short time;
- Could be used instinctively, without need of any training;
- Should be as efficient when used as a stand-alone tool than used within other tools;
- Could be used in any scientific or industrial domain without need of adjustment;
- Should have the same efficiency when used by a single designer than with a group of designers;

- Should facilitate the use of subsequent tools by offering an up-stream support of their completion.

6.2 Tansfer tools

The transferring tools, which are involved in translating a technical problem into a biological challenge and vice-versa, imply idea generation. To fulfill this objective, an ideal transferring tool should

- Only point at a unique solution;
- Be able to strongly enlarge designer(s) knowledge if necessary;
- Allow the designer to completely sub-modularize generated solution(s) to enhance versatility of the generated concept;
- Generate solution(s) with high level of inventiveness.

The practical/operational criteria remain the same as for the abstracting tools.

7. Conclusion

Although bio-inspiration is a well-known instrument for innovation, the problem-solving process that leads to the solution has not yet been exhaustively investigated. Thus, each step of a process of bio-inspiration is quite permissive. The purpose of this article was to understand what bio-inspiration is, by defining its relative concepts and boundaries. Biomimetics would therefore be limited to the methodological aspects of bio-inspiration; bionics would define a discipline which seeks to emulate bioogy through mechanical means; biomimicry would be a philosophy which involves the bio-inspiration part related to sustainability. Following these statements, the article tackled how bio-inspiration can be supported by existing problem-solving tools and processes. A general process for bio-inspiration has been logically extrapolated from literature analysis coupled with several case studies, and it has been compared with a classical problem-solving process. This analogy allows a generalization on the use of problem-solving tools to support biomimetics. Using a similarity with the TRIZ way of thinking, a direct correspondence with TRIZ tools has been presented. Each phase of the proposed process has been classified according to the type of tool that is needed: “abstracting tool”, “transferring tool”, “implementation tool” and “evaluation tool”. For the two first class, an ideal set of features has been defined.

The analysis detailed in the article could be extended to other TRIZ and non-TRIZ tool, especially to identify tools that could fulfill “application” and “evaluation” needs that tools mentioned in the article don’t seem to address. The article focuses on the problem driven biomimetic method, the same work could be performed with the solution driven method.The addition of a framework aiming at quantifying synergy between tools would be a great improvement. That framework would allow designers to identify the number of seqsuential tools needed to fulfill a single step. In the end the work described in this article could also be used as a template to compare qualitively existing biomimetics tools but also methods, with methods being an assembly of tools. It could be a way to compare what means are used and what are their goals. On the bottom line, it could lead to identify biomimetics methodological gaps.

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