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MODELING BIOLOGICAL SYSTEMS TO FACILITATE THEIR SELECTION DURING A BIO-INSPIRED DESIGN PROCESS

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Abstract

The bio-inspired design process implies a multiplicity of actors. Engineers and biologists are usually among them. Mobilize cross-disciplinary and/or highly specialized biologists is a complex task and tools have been developed to address this specificity of the biomimetic approaches. However, the selection of biological model(s) of inspiration does not appear to have yet been tackled. This paper aims at proposing a way to define a benefit/effort ratio for considered biology to technology analogies, which should allow designers to sort these analogies on their own, easing the global biomimetic process. For such need, the paper presents a model revolving around the concepts of ideality and resources coupled with Living System Theory principles. The thorough analysis proposed here shows a consideration on what biological systems are, particularly for a bio-inspired design purpose. This analysis feeds the discussion on how biological systems could be appropriately modeled in order for them to be compared with technical ones, which is the initial need for the described model completion.

Keywords: Bio-inspired design and biomimetics, Design methodology, Biological System, Innovation.

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1 INTRODUCTION

In a world threatened by an extremely strong, strategic and perpetually growing competition, innovation used as a differentiating factor is really important in our modern economies (Paul 2011). Faced with these constraints due to globalization, the cycles of innovations have shortened to such an extent that we now speak of continual innovation (Boer and Gertsen, 2003). Over the same period, a new paradigm came into being. Our societies have been confronted to the finiteness of reserves made available for them by their environment (Tilton, 1996). Due to the paradox between the accelerated obsolescence of our products through the speeding up of the cycles of innovations and the growing environmental constraints, designers now have to rethink their activity so they can offer responsible innovations.

Many technical challenges are still to be solved. Technology seems to have trouble in rising to the challenge of solving these said challenges resiliently. Bio-inspiration and its methodological form, biomimetics, aim at taking advantage of nature's perspective regarding solving problems it came across. This problem solving is based on living things' genetic variability, coupled with the principle of natural selection which allows, over the generations, the emphasis of some characteristics. This whole process leads to a mechanism of trial and error. This mechanism would not be working without the resource which seems to be lacking: time. Without this "time" made available, it consequently seems interesting to try to understand how nature works by getting to understand what the biomimetic process is, thus allowing us to free ourselves from the trial and error mechanism.

First of all this article will explain the various biomimetic processes described in different works, then it will identify a need within the biomimetics toolset and will address it by proposing a consideration upon biological systems specificities and modeling.

2 BIO-INSPIRED DESIGN PROCESS

Some biomimetic problems solving processes, also called problem-driven or techno-push, have been, in this respect, described in various works. Lindemann and Gramann (2004) have offered the bionic procedural; Bogatyrev (2008) hybridized bio-inspired design and TRIZ in a 6 step model; Lenau (2009) proposed the biomimetic as a design methodology model; Helms et al. (2009) proposed a design process providing iterative feedback and refinement loops; Nagel et al. (2014) proposed a model focusing on the functional establishment of a pattern/model of biological models;

Even though showing significant differences (e.g. whether feedback loops are present or not, differences in focus, problem-driven/solution-driven aspect or both, etc.) these various processes share some components (i.e. identification of the technical problem, a transition phase to the biological domain, a research phase of biological models, an abstraction phase of the biological strategie(s), a translation phase from the biology field to the technical one).

These shared elements have led to a model based on the basic outline of mentioned processes (Fayemi et al., 2014):

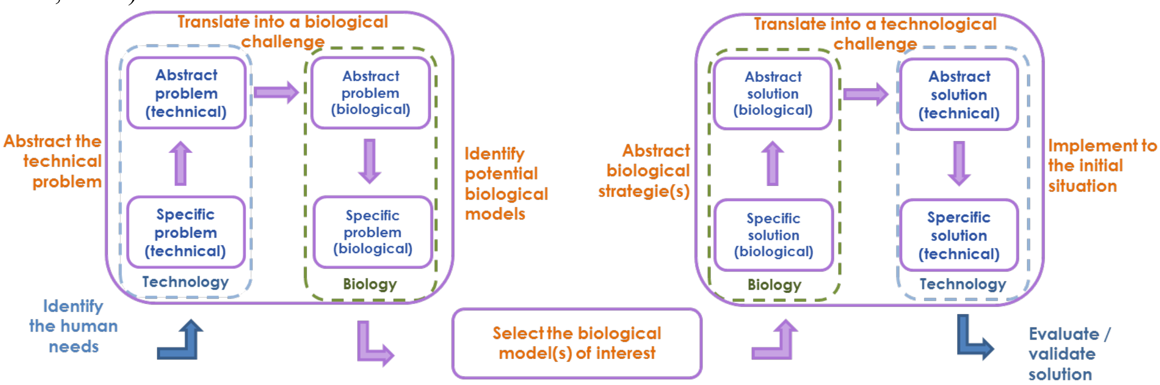

Figure 1. Merged problem-driven biomimetic process (Fayemi et al., 2014)

This procedural model, as shown in figure 1, highlights the need for biological knowledge in two specific places. The first one occurs in the cycle on the left, the one concerning the transition from the technological to the biological field. The contribution of biological knowledge is used here to transpose the abstraction of the technical problem over to the biological field, and then to identify the living systems which could be able to provide answers. Here, the identified need is thus the one of one or several horizontal biologists (i.e. biologist(s) with cross-disciplinary knowledge), able to create pathways between the technical and biological fields with the capability to identify a critical potential relevant pool of living systems. The second biological contribution takes place in the right cycle of figure 1, it leads back biological knowledge into technical field. Here is the need of one or several vertical biologists, experts enough in considered biological system to authenticate the relevance of the analogy, to turn it into an abstracted model and to implement it in the initial problematic situation. The amount of needed experts is based on identified biological systems at the previous step.

The way of acting makes biologists step in the bio-inspired design process at an early stage. However, the population of biologists, being able to play the part of horizontal biologists who control the language and understand both biological and technical issues is very much restricted. It is an illusion to imagine that in the short term, the critical mass of such profiles will be sufficient enough to answer the needs generated by the recent keen interest in bio-inspired design. Although we could think that specialized biologists would be ready to be enlisted because of the enhanced value of their work and because of the financial contribution given by the industry, which is likely to finance their research. The situation was found to be substantially different. Cummings and Kiesler (2005) have highlighted that the specialization on one field led to problems of communication as far as knowledge sharing from specialists to non-specialists is concerned. The process of mobilizing these vertical biologists proves to be tedious as well as time consuming.

Democratization of bio-inspired design, in the light of these facts, seems to ask for a careful consideration on how the transfer of knowledge and the involvement of biologists could be eased in the heart of its process.

3 PROPOSED RESEARCH

During a knowledge transfer process, a lot of barriers exist: lack of mutual understanding of culture, context, constraints, goals; insufficient reward system (Siegel et al., 2004); mutual understanding of processes and outcome; confidentiality (Bruneel et al., 2010). In order to overcome these barriers, researchers have, over the past decade, developed tools and methodologies to reduce the need of biologists and/or ease the implementation of biological knowledge within the Bio-Inspired Design process. Regarding the identification of the pool of potential biological models of inspiration, Vandevenne et al. (2011), Vattam et al. (2011), Vincent (2014), Nagel (2014), Shu and Cheong (2014) proposed different approaches, whether they are information-processing, natural language, functional or TRIZ based. Nevertheless, no methodology or tool tackling the selection of the right biological model(s) has been found. Therefore, the detailed research is specifically addressing this step.

3.1 Purpose

As shown in the biomimetic process of section 2.2, a pool of biological systems which would actually provide an answer to an initial technical issue is defined. Thus, each of these potential “solution systems” has to be researched, and this, thanks to the assistance of a vertical biologist. For every biological system identified the same number of vertical biologists would potentially have to be identified, contacted, initiated to the approach and motivated. The amount of work produced is substantial.

Another element comes into consideration. In fact, among all the identified biological systems, only one, or in general a small number of these systems, will be used as a source of knowledge during the phase of transfer from the biological to the technological field. Regarding all the work which has been fulfilled, only a small amount has been useful. It is moreover highly probable that this would give rise to frustration among biologists whose systems covered by their expertise have not been selected.

To address this issue, we offer a model which tries hard to allow people, without any specific biological knowledge, to arrange by relevancy the identified biological systems on their own. This approach do not intend to exclude the vertical biologists from the biomimetic process, but only to delay their intervention.

This scheduling thus allows designers to call up vertical biologists sequentially, thanks to a probability of good match between initial problem and identified living system. Eventually, it is a substantial decrease in terms of work and effort to apply to the completion of the biomimetic process.

3.2 Proposed Model

The model revolves around the concept of ideality. According to Altshuller (1984), every technical system can reach its ideal state. This ideality, or degree of ideality has been described in mathematical terms:

$$I = \frac{\sum Fu}{\sum Fh + \sum Fc} \qquad (1)$$

According to this equation (1), a system, to reach its ideal state, can increase its numerator (increasing its useful function(s) (Fu)) by taking advantage of unutilized resources to provide additional useful features) or reduce its denominator (reduce costs (Fc) by eliminating unutilized resource(s) or using less expensive resource(s) and/or reduce harmful effect(s) (Fh)). In our model, the concept of ideality is used as a baseline allowing us to measure the positive or negative impact of a solution given out by a biological system related to an initial technological problem.

Several knowledge transfer strategies may be considered to identify analogies (Zlotin and Zusman, 2005):

- Systems that perform function(s) similar to the function(s) of the given system.
- Systems that perform function(s) capable of replacing the function(s) of the given system or its subsystems.
- Systems that perform function(s) opposite to those of the given system.
- New idea(s) and technology that could help carry out auxiliary function(s) or add new feature(s) to the given system (i.e., enabling technologies).
- Idea(s) and concept(s) for eliminating and/or preventing drawbacks or other undesired effects associated with the given system.

The fact that analogy should prioritize function enables the quantification of the latter, corresponding to a theoretical estimation of the useful function(s). The useful function(s) can thus correspond or not to the requirements (e.g.: In the Eastgate centre building case, designers were looking for a passive cooling system; termites' mounds do provide a passive cooling system). The characterization of the useful function(s), the benefit, leads to a better understanding of the potential effect of the analogy on the final design outcome. It also defines a filter which ensure that considered analogies show relevancy to the initial problem statement.

The model relies on the definition of a technological space, corresponding to the initial issues, and on a biological space, corresponding to each system likely to offer one or many solution opportunity/ies.

A knowledge transfer can be made through three different ways:

- Direct transfer: technology space and biology space are identical. Strongly unlikely to occur.
- Transfer with adaptations: solution space has to be adapted to fit the problem space.
- Hybridization: both spaces are adapted to fit each other's. Out of scope, related to bio-assistance.

Considering the types of adaptations required, the knowledge would be more or less easy to transfer.

The model foresees enabling the sorting of the various considered analogies thanks to the emphasis on a benefit/efforts-risks ratio.

In order to achieve this sorting, the definitions of technological and biological space are compared thanks to the use of resources, another concept described by TRIZ (Altshuller, 1984). A technical system has a whole range of resources available in order to achieve its ideality. Zlotin and Zusman (2005) consider the following types of resources for a system: substances resources, field resources, functional resources, space resources, time resources and informational resources.

The more the biological and technical systems work while using resources which are approximately the same, the easier the transfer from biological to technical. The quantification of the necessary adaptations is thus able to enable the identification of the efforts to implement as well as the potential transfer failures (e.g.: In the Eastgate centre building case, space resource differed, leading to scaling issues). Three scenarii are conceivable:

- Technological system does not provide enough resources to implement the biological principle.
- Resources provided by the technological system induce too many negative side effects.
- Resources provided by the biological system induce too many negative side effects.

Thus, the principle of this comparison is based on a need for modeling of both the technical system and the biological system(s).

Modeling technical systems
Regarding the bio-inspired design, two main approaches of modeling technical systems have been investigated. The former is based on the ontology FBS (Gero, 1990), which describes the design process in terms of Functions, Behaviors, Structures, and Design Descriptions. The latter is based on TRIZ, the theory of inventive problem solving. Chen and Chen (2014) have described technical systems through the substance-field model.

Modeling biological systems
Biological systems modeling proves to be more complex. According to their nature, biological systems are often multifunctional and their links with their environment are complex. Consequently, it is difficult to achieve some modeling on a biological system with the right degree of abstraction. This abstraction has to be enough in order for the modeling to be understandable, but sufficiently accurate not to lose the relative constraints. Since, it appears as necessary to define clearly the particularities of the biological systems.

3.3 Specificities of Biological Systems

The consideration of very specific characteristics of living systems and their nested organization are factors which can lead to the misconception of what is a system. For example the word "system" can refer to the interaction of the object of the abstraction with its environment, but in some cases it can also refer to the network of processes within this object. To solve this issue, we suggest to keep the world "system" only to refer to the object of analysis itself and use the General System Theory (Bertalanffy, 1968) as a common ground for both biology and technology. The initial step would be to apply this very simple abstraction scheme which any open system, biologic or not, must follow:
Like any system, all open systems necessarily have a boundary, inputs, outputs and a throughput function, see figure 2. All systems also have a boundary that can be physical or symbolic. Along with the entire system, its parts are seen as *subsystems*. Considering the different parts, the whole is seen as a *supersystem*. This organization is valid for any dynamic system, regardless of the particular domain in which the system is related to and also coincides/corresponds to the Altshuller's (1984) system definition.

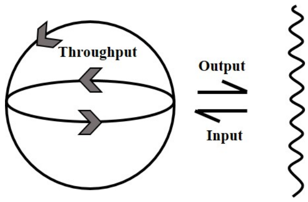

Figure 2. General System Theory, input, output, throughput

We could abstract:

- Inputs: the matter, energy and information interacting with or entering the system's boundaries
- Throughputs: the processes used within the system to convert or transform inputs from the environment into products which are usable by either the system itself or its environment.
- Outputs: The product which results from the system's throughputs.

Biological systems are non-linear open systems, they are dissipative structures far from the thermodynamic equilibrium. As shown by Ilia Priogine (1997), they are able to create and maintain, at least for a certain time, their physical and physiological integrity and they do so by continuously exchanging matter, energy and information with their environment. They are goal directed in a way that they need to survive and at least for the organism level, reproduce (or maintain their resilience at higher levels of organizations such as ecosystems). A very important aspect of open systems, is that some outputs could be directly or indirectly used as new inputs (feedback loops). Feedback loops are used to make the necessary changes in order to survive, grow or reproduce and explain emerging properties at higher levels of organization (*i.e* organism compared to cells) explaining that "the sum (system) if more, then, the addition of the properties of its parts (subsystems)". The peculiarity of any open systems (living or non-living) is that they interact with other systems outside of themselves. Each level in the hierarchy of supra systems, systems and subsystems, has its own laws, which cannot be derived from the laws of the lower level. Continuous flows of matter, energy and information cross or interact with the boundary of the living system (cell membrane, skin, ecosystem's border, social structure, etc.) and are processed inside the system (throughput) into structures, processes and networks of relationships between both. Doing so, biological systems create order (decrease entropy) inside and export waste (export their entropy) and other products in their supra system (or environment).

In technological systems, we usually expect the products (outputs) and the system of production (throughputs) to be different aspects of the overall process. It is not the case for biological systems: they are *autopietic*. The theory of *autopoiesis* was coined by Matarana and Varela (1980) and they have created the term 'Autopoiesis' from "auto" = self, and "poeisis" = creation. Their major contribution was to clarify that living systems consist of a network of processes of production (and transformation and destruction) which realize and regenerate the network which produced them. Thus, life is understood to have a dynamic, cyclic, and self-maintaining organization.

This has many implications if we need to understand biological processes and related outputs. These interactions are not simple because they are based on complex networks of interdependencies inside the system, and between the system and its supra system. But in order to solve specific human problems we could consider some part of the system's complexity as a "black box", something which takes in input, and produces output, without us being able to explain what happens in between. In contrast, if we could explain the system's internal processes linked to the production of a biological artefact of interest, we might call it a "white box".

An important point would be to define if the system of interest is *autopoietic* by itself or the result of another *autopoietic* supra system. For example a specific bone could be almost considered as a closed system which is the outcome of the *autopoietic* supra system "individual". We could decide that if the structure and shape of the bone is our core interest, we consider that even if we are aware that *autopoietic* processes are involved, they could be for a time left in the conceptual "black box" and we will explore processes inside this black box only if our abstraction led us to do so. But we should emphasize that this conceptual black box could hide very important processes explaining some key characteristics of the structure of forms. For instance, during the growth process, the hierarchical structuring of shapes and microstructures are created in a stepwise manner but using a unique process. The construction of complex organs is often based on very similar building blocks, like collagen fibrils in bones which have units with a few hundred nanometre thickness and can be assembled to a variety of bones with very different functions (Currey, 2002). Such growth process is part of *autopoiesis*, environment sensitive, leading to final products which can be different considering the environment changes.

Maturana and Varela define a living system as "an organized structure", structure being "components and relations in a particular unity or "thing" (Matarana and Varela, 1980). They define "organization" as "existing relations among component of a system for it to be a member of a specific class". Another important aspect of the Santiago theory developed by Maturana and Varela is the concept of cognition, which is for them equivalent to "living process" or the act of "doing". Capra (1997) suggests redefining the definition of structure as "the physical embodiment of the system's pattern of organization"; and defines pattern of organisation as "configuration of relationships that determines the system's essential characteristics". Life process is, for him, "activity involved in the continual embodiment of the system's pattern of organization » (similar to cognition as defined by Gregory Bateson (1979)).

Both authors refer to living systems, and thus *autopoietic* systems. But in biomimetics, the system analysed is, most of the time, not *autopoietic* but an agent of what is, or used to be, an *autopoietic* supra system. Understanding how our system of interested is related to a nested hierarchy of *autopoietic* sub or supra systems is key (*i.e* cell, organism, group, society, ecosystem).

To make the juncture between General System Theory, TRIZ terminology and *autopoiesis*, we propose the following definitions:

- System: organized structures inside a boundary and involved in a network of processes in order to achieve something (goal).
- Structure: components organized in space and time in a particular shape (form). If the system is *autopoietic*, it is the physical embodiment of the system's pattern of organization.
- Pattern of organization: configuration of network of relationships which determines the system's essential characteristics inside the system, or involving other components in the system's environment.

- Process: activity involved in the pursue of the system's goal, inside the system itself (throughput) or with components of its environment. If the system is *autopoietic*, it is the activity involved in the continual embodiment of the system's pattern of organization (life and cognition).

3.4 Biological systems modeling

Modeling biological systems is a rather complex task. Compared to technical systems, biological ones can hardly be seen as parts associated to functions. During the course of evolution, living systems have responded to a multitude of dynamic boundary conditions, which we often don't a priori know, but might all be important to explain the development of the structures and patterns observed. This implies that, biological systems have been optimized under certain conditions and unknown requirements, making it hard to understand why a living system is organized that way. Thus, a provided function should not be the starting point of the identification and the selection of a possible analogy and therefore of the biological abstraction.

3.4.1 Existing approaches

Several attempts to model biological systems within a BID process have been identified in literature. The SAPPhIRE model (Chakrabarti et al., 2005) has been developed to model a system and its environment with a high abstraction level. It prodives an holistic representation and allow designers to identify different levels of abstraction to represent biological information (Chakrabarti et al, 2014).
Nagel (2011) modeled biological systems with their three most basic instinctual actions (i.e. protect, reproduce and sustain) as the entry point. Vattam et al. (2011) developed a knowledge-based CAD system called DANE (Design by Analogy to Nature Engine). The DANE approach focuses on describing in a detailed way the internal structure and functions of a system. Based on both SAPPhIRE and DANE, Baldussu et al. (2014) proposed the integrated SAPPhIRE-DANE model, combining both the function and causal approaches in a single model, correlating components of a system to parameters.
The main objective of these three models is to provide a functional and/or causal models of living systems, allowing designers to facilitate the transfer of biological knowledge to the technical domain. This objective differs from the one of the model detailed in this article, which does not focus on the transfer step of biological to technical but on its previous one, the selection of the right analogies. Given this difference, these models may present issues to fit the research purpose. By providing a causal explanation of how a system accomplishes a function, these models analyze solutions. This specificity leads the comparison of a problem description (i.e. technical system models) with a solution description (i.e. biological system models).

3.4.2 Modeling biological systems through Miller's Living System Theory

In order to model biological systems to allow a direct comparison with technical ones, a new model is tackled. This model is based on the Miller's Living System Theory (1978) which is a subset of the general systems theory, tackling the living ones. It offers a frame focusing on how living systems can be described as matter and energy organization schemes. Miller's analysis range across 7 systemic levels (i.e. cell, organ, organism, group, organization, society, supranational system), identifying 19 scale-invariant subsets of a living system.

Table 1. The 19 scale-invariant subsets and their application to human cardiac muscle (Miller, 1978)

Subsystems which process both matter-energy and information applied to human cardiac muscle (HCM)			
Reproducer		*Nucleus*	
Boundary		*Cell membrane*	
Subsystem which process Matter-Energy applied to HCM		**Subsytems which process information applied toHCM**	
Ingestor	*Cell membrane*	Input transducer	*Subsynaptic region*
Distributor	*Endoplasmic reticulum*	Internal transducer	*Enzymes & repressors*
Converter	*Enzymes (mitochondria)*	Channel and net	*sarcoplasmic reticulum*
Producer	*Nucleic acids (ribosomes)*	Decoder	*Subsynaptic region*
Matter-energy storage	*Glycogen granules*	Associator	-
Extruder	*Cell membrane*	Memory	-
Motor	*Myofibrils*	Decider	*Genes (nucleus)*
Supporter	*Myofibrils*	Encoder	*transmitter producers*
		Output transducer	*prejunctional region*

The initial purpose of the theory was to identify through a cross-level analysis systemic hypotheses that could be tested thanks to the model (e.g how a cell could react and solve an information input overload). However, as shown in table 1, the theory serves here, through its 19 scale-invariant subsets, as a way to draw an abstract model of biological systems. This abstraction model tends, on the philosophical perspective, to the Altshuller's Law of System Completeness (1984). One of the downside of Miller's theory is the lack of measurement tools to address the modeled systems, which is here compensated by the use of resources as defined by Zlotin and Zusman (2005).
Such model should be able to provide the following specificities:

- Address the different considered biomimetics systemic levels (e.i. system, structure, pattern of organization and process).
- Be compatible with technical systems description.
- Can be used by designers with limited biological knowledge.
- Can integrate several functions of a biological system.
- Provide a potential for scalability.

4 EXPERIMENTATION

In order to assess the disclosed biological modeling viability to support the step of analogy selection, the model should be verified by a laboratory experiment. The basic parameters of the experimentation, which should ensure that the established guidelines are met, will be outlined in the following paragraphs.

4.1 Hypotheses

As shown by the established guidelines, several hypotheses can be considered. For the present article, the following hypotheses will be addressed:

- A pattern for modeling living systems irrespective of their biomimetics systemic level can be established.
- The model is suitable for a various range of profile (ranging from high degree of biological knowledge to limited).
- The model leads to the identification of functional subsystems and thus, to the characterization of their resources.

Meeting these requirements will ensure that this model is suitable for its bio-inspired design purposes.

4.2 Experimental setting

To investigate the mentioned hypotheses, a laboratory experiment is set with the following parameters:

Systemic levels

The experiment will tackle each considered systemic level, as mentioned in section 3.3. The examined biological systems will be the emperor penguin for the systemic level, the Cell membrane for the structure level, the temperate deciduous forest for the pattern of organization level, and the protein synthesis for the process level.

Population

The experiment will include several types of participants. The first one will be vertical biologists, one per systemic level, who will initially define the positive control (i.e. modeling the biological system belonging to their expertise). Vertical biologists will also define a body of text, which according to them, contains sufficient information for other participants to model biological systems. The others types of participants will be horizontal biologists, two per systemic levels, biology students, twelve groups of two students, designers, two per systemic levels, and engineering students, twelve groups of two students. For each profiles of participant, one person, or group for students, will be used to define a negative control by modeling systems without the model.

Process

In order, for the participants, to get aware of the different concepts and theories, an initial 1 hour training upon TRIZ and Living System Theory will be provided. Following this training the modeling of the considered biological system will be tested. No time limit will be set for the establishment of the reference model by the vertical biologists while there will be a 2 hours limit for other participants. At the end of the experiment, participants will be asked to fulfil a questionnaire in order to complete information on difficulties met during the modeling process and obtain their perceived value of the given model.

Evaluation of results

The results of the modeling systems will be evaluated according to their match with vertical biologists' referential modeled systems.

The focus of the evaluation will rely both on the quality (i.e. impact of the gradient of biological knowledge on the use of the model) and on the quantity (i.e. amount of participants able to use the model) of the generated biological system models.

5 CONCLUSION AND FURTER RESEARCH

A new model focusing on facilitating the selection of the right analogies is described through the article. By hybridizing concepts of ideality, resources and system modeling, designers should be able to rank the identified biological systems themselves. Beyond this specific focus on the selection of biological system(s), the model also allows designers to pre-analyze biological systems. This pre-analysis is conducted, not towards a specific function, but with a focus on the global system. In this respect, the described model could also be seen as a translation tool, allowing people with few or non-biological background to establish a base of common language that should ease the contact initiation and the collaboration with vertical biologists. Considering the established biomimetic process mentioned in section 2, sorting the envisaged analogies could theoretically reduce by half, the abstraction requirements. Designers could thus perform biomimetic projects with a single abstraction and concretization step, reducing the complexity of such approach.

The initial validation of the model has to be made through the study of the biological system modeling. Several other experiments are required to validate the whole model. Following this initial experiment, another one should assess the criteria used to compare technical to biological analogies. Finally a third experiment should focus on the process automation, which should enhance the model's scalability. This automation should require the development of a specific ontology revolving around the scale-invariant subsets.

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