DOI: 10.13009/EUCASS2019-796

8th european conference for aeronautics and space sciences (EUCASS)

How could nature inspire solutions for aeronautics and space sciences?

S.G. Hoornaert, N. Lassabe°, C. Finzinger [#], M. Penalva °°, A. Pechstein[£], J. Chirazi[@], and F. Mathis***

** Morpho-Biomimicry Research & Innovation Centre*
23 Av. Fr. Ferrer, 4030 Liege, Belgium - biomimicry.be@gmail.com
° ONERA/DTIS - The French Aerospace Lab
2 Av. Ed. Belin, 31000 Toulouse, France – nicolas.lassabe@onera.fr
[#] Finzinger architecture
60 Bd. Aristide Briand, 46300 Gourdon, France - celine@finzinger.com
°° Fungus Sapiens
Lieu-dit Roqueville, 31540 Bélesta-en-Lauragais, France - fungus.sapiens@gmail.com
[£] Biomimicry Academy & phi360 Consulting Berlin
Kiefernsteg 6, 14532 Stahnsdorf, Germany - pechstein@biomimicrygermany.de
[@] Biomimicry Institute
4196 Cleveland Av., San Diego, CA 92103, USA - jchirazi@gmail.com
*** Ecole Européenne de la Transition Ecologique (ETRE)*
Lieu-dit Bordeneuve, 31370 Lahage, France - contact@ecole-transition.eu

Abstract

Life performs R&D since about four billion years using endless combinations with a ruthless crash-test: Reality. Nature's genius may help to solve problems. For this, engineers and biologists need to collaborate. Different methodologies can facilitate this interdisciplinary collaboration. Bringing together information from different disciplines enables understanding of different perspective, promote critical thinking, and consider alternative solutions. As Buckminster Fuller famously observed, a system is greater than the sum of its part. By mixing distant fields of knowledge, 1+1=3 becomes understandable. This may open a new era of highly efficient innovation in aeronautics and space science.

1. A little bit of perspective

"*Human subtlety will never devise an invention more beautiful, more simple or more direct than does Nature because in her inventions, nothing is lacking and nothing is superfluous*".
— Leonardo daVinci

Our solar system accompanied by its planet procession, including ours, appeared about 4.5 billion years ago. For us mortals, it is difficult to conceive such long durations. If we postpone this duration to an Earth year, it allows us to see our story differently. Consider that our planet was born on January 1st and we are now December 31st midnight. Life appears end of February. Multicellular organisms appear mid-August. The Cambrian biodiversity explosion occurs mid-November with the apparition of Fungi, Fishes, Plants and Insects. During December appear Amphibians, Reptiles, Mammals, Birds then Flowers. The first hominids walk the 31st of December at 11am. *Homo sapiens* appear at 23h36. Agriculture is invented at 23h59 and the industrial revolution occurs at 23h59 and 58 seconds.

We are a very young species. All human history would take place in the last half hour of the last day. The industrial revolution would take place in the last 2 seconds. This little perspective helps us better realize that during this gigantic period of time, life had the opportunity to test an almost infinite number of possibilities that have undergone the evolutionary pressure, a radical crash-test: the Reality.

The beauty, power and immensity of nature are an inexhaustible source of inspiration. In mythology, there are many examples of bio-inspired solutions: Daedalus and his son Icarus, Hermes, Pegasus, etc. Among the first traces of applied Bio-inspiration, Leonardo daVinci, in the 15th century, was inspired by the flight of birds to imagine the ancestors of our planes. Bio-inspiration has sporadically led to innovations such as Velcro, which was invented by

DOI: 10.13009/EUCASS2019-796

Georges de Mestral inspired by the observation he made about the burdock fruits attached to the hair of his dog. Water lily leaf veins could have inspired the Crystal Palace, one of the largest glass and metal structures, invented by Joseph Paxton for the 1851 World Expo. For another world expo, the Eiffel tower build in 1889 was inspired by femoral bones structures. These innovations inspired by nature were mostly accidental and sporadic. Otto Herbert Schmitt, an American biophysicist and inventor of genius, would have coined the term “Biomimicry” in his doctoral thesis already in 1957. In the early 1970s, two British scientists from very different disciplines began a collaboration at the University of Reading. Julian Vincent, zoologist and Georges Jeronimidis, engineer, are interested in the biomechanics of plants and animals. They created an interdisciplinary department to strengthen the integration between their respective disciplines: the “Center of Biomimetics” at the U/Reading was born. However, it was not until the publication of Janine Benyus’s book “Biomimicry - Innovation inspired by Nature” (1) in 1997 that the fundamentals of biomimicry and bio-inspiration were disseminated more widely.

Since then, the volume of academic research in this area has exploded in recent years, from 100 annual articles in peer-reviewed journals in the mid-1990s to over 3000 in 2013, and this continues to increase. Much has been done and many methodologies have been developed to facilitate this interdisciplinary approach. Among these advancements, at the ISO level, standards have been established. The different working groups gathered around several themes. During all these meetings, gathering international experts of different specialties, and also in a general way, in the networks using the bio-inspired approach around the world, different restraints that impede this approach to more widely use were identified. One of the essential identified problematic: interdisciplinary cooperation hardly exists. One of the reasons could be mainly because the language used in one domain does not always correspond to the language used in other domains. There is also a major and frequent issue in the differences of goal (the “scientific question to be answered”). Engineers and Biologists do not necessarily have interest in the same questions. So, the challenge could be sometime to remain motivated by each other’s questions. Engineers are not "wired" like biologists and have radically different approaches. Because of all this, they are, unfortunately, very often unable to talk to each other and thus collaborate and solve problems together. However, bridges can be established between these disciplines to bring out new, and often, revolutionary concepts. Examples of such beneficial collaboration emerge. For this purpose, some effort needs to be done to understand each other. Biologists need to acquire tools of other disciplines. For engineers, this may implies understanding of some basic life’s principles.

Bio-inspired innovation can help us be much more effective. At the environmental level, these innovations would enable us to improve our resilience to climate change, can regenerate our ecosystems and improve the use of natural resources. At the social level, we are witnessing the emergence of new business models, new values and new technologies. At the economic level, these innovations allow a better differentiation in order to improve the competitiveness of companies but also, and especially, optimization of the production processes. Circular economy and industrial ecology are beginning to be better known even though the links with the bio-inspiration are still actually underestimated.

About “return on investment”, the NASA Langley research report quoted already in 2002 (*2*): “*Natural systems tend to minimize "cost" for maximum "gain" [...]. It is clear that these biological principles can also be applied to engineered systems to minimize cost and maximize gain (function). In fact, we can exploit these concepts even for deep space exploration where biological systems have yet to be discovered*”.

Scientific evidences show more and more obviously that the global challenges we are facing are dramatic (3, 4). What we can observe around us, in nature, is the result of this unimaginable R&D. Each living organism is like a book full of knowledge rich of about four billion years and biologists strive to read and understand these books. Engineers, architects, designers solve problems everyday (thanks to them) but they also need solutions for the coming challenges. They are, most of the time, unaware of the knowledge lying in this huge library that is nature. Would not it be wise for engineers, architects, designers and biologists to talk to each other?

2. Life’s principles

“Nature does nothing uselessly.”
— Aristotle*,*

Life’s principles are operating rules that "create conditions conducive to life” (5). These rules have longtime been applied unconsciously by humans, until the advent of large-scale agriculture and the industrial revolution, which then led to a more or less rapid abandonment of these rules. Inspired by pre-established works (6), the Biomimicry 3.8 network has published a list containing all these principles of life, as shown in Figure 1.

DOI: 10.13009/EUCASS2019-796

The living has developed these operating principles under the influence of four "Earth's operating conditions".

- *Sun, water and gravity:* the sun's light has allowed life to develop by providing the necessary energy for the process of photosynthesis. The living has developed in water, a molecule essential to life since the cellular processes of all living beings depend on this formidable solvent. Finally, gravity keeps us firmly rooted on the planet.
- *Non-equilibrium dynamics:* the terrestrial system in which life has developed is characterized by its constant non-equilibrium nature. This means that the conditions of the environment in which living things evolve are constantly necessarily changing. Therefore, to deal with this impermanence, living organisms have had to develop a constant adaptability.
- *Limits and boundaries:* the living has appeared in a world, which is in essence limited and finite. The only resource that is almost infinite is solar energy.
- *Cyclic processes:* many events that influence the Earth are cyclical and thus in a regular pattern (seasons, alternation of day and night, etc.). Nature operates these cyclic processes for profit rather than trying to eliminate them.

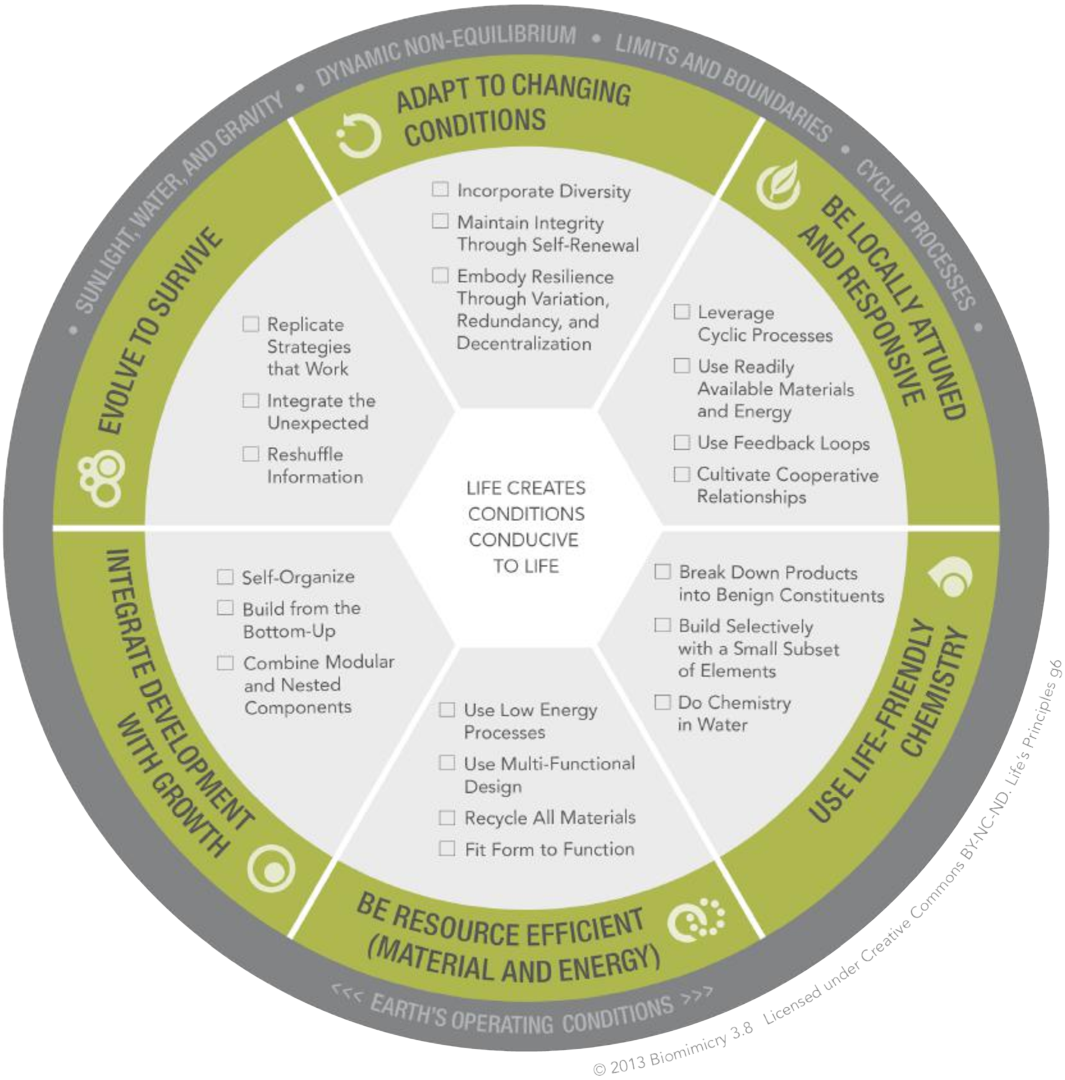

Figure 1: Life's principles according to the Biomimicry3.8 network

This list of living principles is divided into six principles, each of which has three to four underlying sub-principles.

1. *Evolve to survive:* continually incorporate and embody information to ensure enduring performance. The organisms live in symbiosis with their environment while remaining autonomous. They are able to perceive and adapt to changes in their habitats. (If these behaviors are extremely complex, their study and their

DOI: 10.13009/EUCASS2019-796

transposition in the field of technology open very promising doors: programmable materials, self-assembling robot, Internet of Things, etc.).
  - Replicate strategies that work: repeat successful strategies.
  - Integrate unexpected: integrate mistakes in ways that can lead to new forms and functions.
  - Reshuffle information: exchange and alter information to create new options.
2. <u>*Adapt to changing conditions:*</u> appropriately respond to dynamic contexts.
  - Incorporate diversity: include multiple forms, processes, or systems to meet a functional need.
  - Maintain integrity through self-renewal: persist by constantly adding energy and matter to heal and improve the system.
  - Embody resilience through variation, redundancy and decentralization: maintain function following disturbance by incorporating a variety of duplicate forms, processes, or systems that are not located exclusively together (Fulfill multiple "good enough" functions instead of only one "perfect").
3. <u>*Be locally attuned and responsive:*</u> fit into and integrate with the surrounding environment. (Leaves of trees are able to collect solar energy efficiently to turn it into useful energy without rare metals importation from the other side of the world).
  - Leverage cyclic processes: take advantage of phenomena that repeat themselves.
  - Use readily available materials and energy: build with abundant, accessible materials while harnessing freely available energy.
  - Use feedback loops: engage in cyclic information flows to modify a reaction appropriately.
  - Cultivate cooperation relationships: Find values through win-win relationships.
4. <u>*Integrate development with growth:*</u> invest optimally in strategies that promote both development and growth. (Honeycomb structures and abalone shells are examples of hyper-resistant structures built from small amounts of abundant and soft materials.)
  - Self-organize: create conditions to allow components to interact in concert to move forward an enriched system.
  - Build from bottom-up: assemble components one unit at a time. These assembled elements can then have a top-down action.
  - Combine modular and nested components: imbricate multiple units within each other progressively, from simple to complex.
5. <u>*Use life-friendly chemistry:*</u> use chemistry that supports life processes. (Spiders are able to make stronger cables than our best Kevlar from flies, in water and at room temperature.)
  - Break down products into benign constituents: use a chemistry in which decomposition result in no harmful byproducts.
  - Build selectively with small subsets of elements: assemble relatively few chemical elements (mainly C, H, O, N, P and S) in elegant ways.
  - Do chemistry in water: use water as a solvent.
6. <u>*Be resource efficient:*</u> skillfully and conservatively take advantage of resource and opportunities. (Circular economy, ecological industry, are examples of this approach)
  - Use low energy processes: minimize energy consumption by reducing requisite temperature, pressure, and/or time for reactions.
  - Use multi-functional design: meet multiple needs with one single solution.
  - Recycle all materials: keep all materials in a closed loop.
  - Fit form to function: select a shape or a pattern based on need.

3. Biology vs (actual) Technology

"Men argue. Nature acts."
— Voltaire

In 2006, a team of biomimetic researchers led by Julian Vincent published in the *Journal of the Royal Society Interface* an article entitled *Biomimetics: it's practice and theory*, devoted to the fundamental differences between technology and biology in problem solving. The team proposed a logical framework articulated around the following axes: to produce (need of energy and information), somewhere (space and time) and objects (substance and structure). They analyzed thousands of examples from biology and engineering by adapting the TRIZ method (Russian acronym for inventive problem-solving theory), a set of tools to facilitate the translation of technical solutions of a domain to another. This study highlighted significant differences between the two disciplines at the problem solving methods, quantifying them according to the scale (from nanoscale to macroscale). These data were synthesized in two charts illustrating the key differences in the design, manufacture and innovation between the living world and the anthropic world. As detailed in the two diagrams in Figure 2, the technology tends to solve its

DOI: 10.13009/EUCASS2019-796

problems with energy reinforcement at the nanoscopic scale, matter at the millimeter scale and space at the macroscopic scale. On the other side, nature presents a much more homogeneous diagram. This increased homogeneity induces, in comparison with technology, a much greater use of structuring, temporality and information as a mode of resolution. (For example, at nanoscale level, technology uses high temperature, high pressure and many toxic components to build silicon-based microprocessors. Nature, at room temperature and in water, is able to create even thinner and subtler silicon-based structure within the *Radiolaria* branch).

The transfer of properties, mechanisms and principles from the field of biology to that of technologies necessarily requires reasoning by analogy. Along with materials and manufacturing, shape, surface and structure are key factors in both creative design and engineering design. It took several years to grasp the range of possibilities that these two different graphs have for design. Biomimicry sheds new light on the relationship between materials, form and function, prompting us to change the paradigm to inspire us more in the living world in the future.

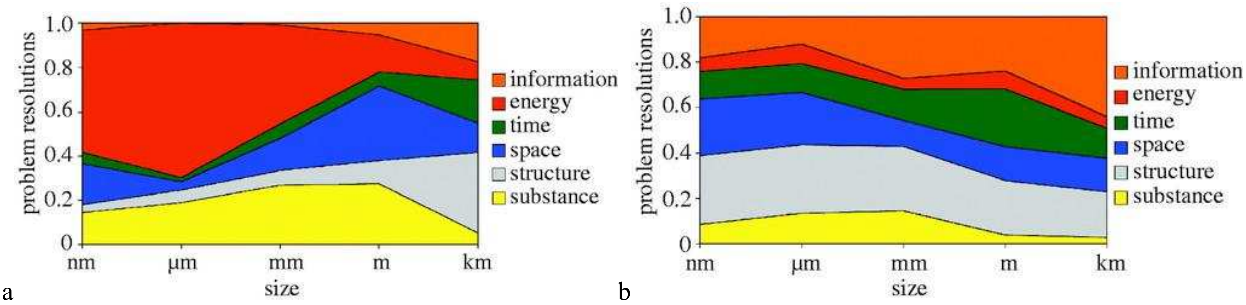

Figure 2: Comparison of resolution mode between technology (a) and living (b) (7)

To solve problems, we mainly use heat, beat and treat. Our way of solving problems is inadequate and lead us to major crises: climate changes, loss of biodiversity, desertification. These crises are such that we are witnessing the collapse of our ecosystems: the 6th massive extinction (The last was 65 million years ago when the dinosaurs disappeared). A radical change in the way we design solutions must therefore be put in place. Could not nature be a source of inspiration?

4. Bio-inspiration

"Nature is not a place to visit. It is home."
— Gary Snyder

Bio-inspiration involves a radical change in the way we look at what surrounds us. It's about getting a more humble position and seeing what we can learn from the living around us. We usually name organisms, know their characteristics, determine their places of life, ecosystem, etc. Here, it is more about seeing what we can learn from nature as if it was a mentor. And so, ask yourself the question: "What are the solutions that life has put in place throughout its evolution to solve this kind of problem?"

4.1 Different level of inspiration

Three level of inspiration have been defined: Form, process and systems.

1. *Form (shape, surface, texture):* this is the first and simplest ways to get inspiration from nature, based on the study of forms, both at macroscopic and microscopic level. Most of the industrial biomimetic applications available on the market today are at this level. This level does not necessarily imply a "sustainable" approach. (E.g.: self-cleaning surfaces - lotus leafs; Velcro – burdocks; high speed train Shinkansen500 – kingfisher, owl, penguin; antifouling - sharkskin, etc.)
2. *Process (and material, a series of operation):* since the industrial revolution, a large majority of our materials are produced at very high temperatures (often several hundred degrees) and at high pressure, while using residual toxic solvents. Paradoxically, living organisms are able to produce at ambient temperature and pressure materials (glass, cement, etc.) whose performances are comparable (or even better) to those we produce, using a limited number of chemical elements: more than 96% of living matter consists of six basic atoms: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur. (E.g.: energy production – photosynthesis; hyper resistant textile – spider; non-chemical adhesive – gecko; air regulation – termite mount; etc.)

DOI: 10.13009/EUCASS2019-796

3. _Ecosystems (a network operating together in an ongoing cycle):_ this time, the object of study is no longer the species but the relationships between species, and how they allow the ecosystem to be dynamically stable and sustainable. Subsequently, biomimetics will derive a whole series of operating rules that explain the sustainability of these ecosystems. This level does not imply disruptive technologies and so can be easily applied. It is indeed much more about organizational changes and information exchange. This third level of inspiration thus applies to spatial and temporal scales higher than the first two levels. (E.g.: Circular economy, industrial and territorial ecology are becoming more renowned but these approaches could be greatly improved if directly inspired by the circular functioning of ecosystems).

4.2 Push or pull

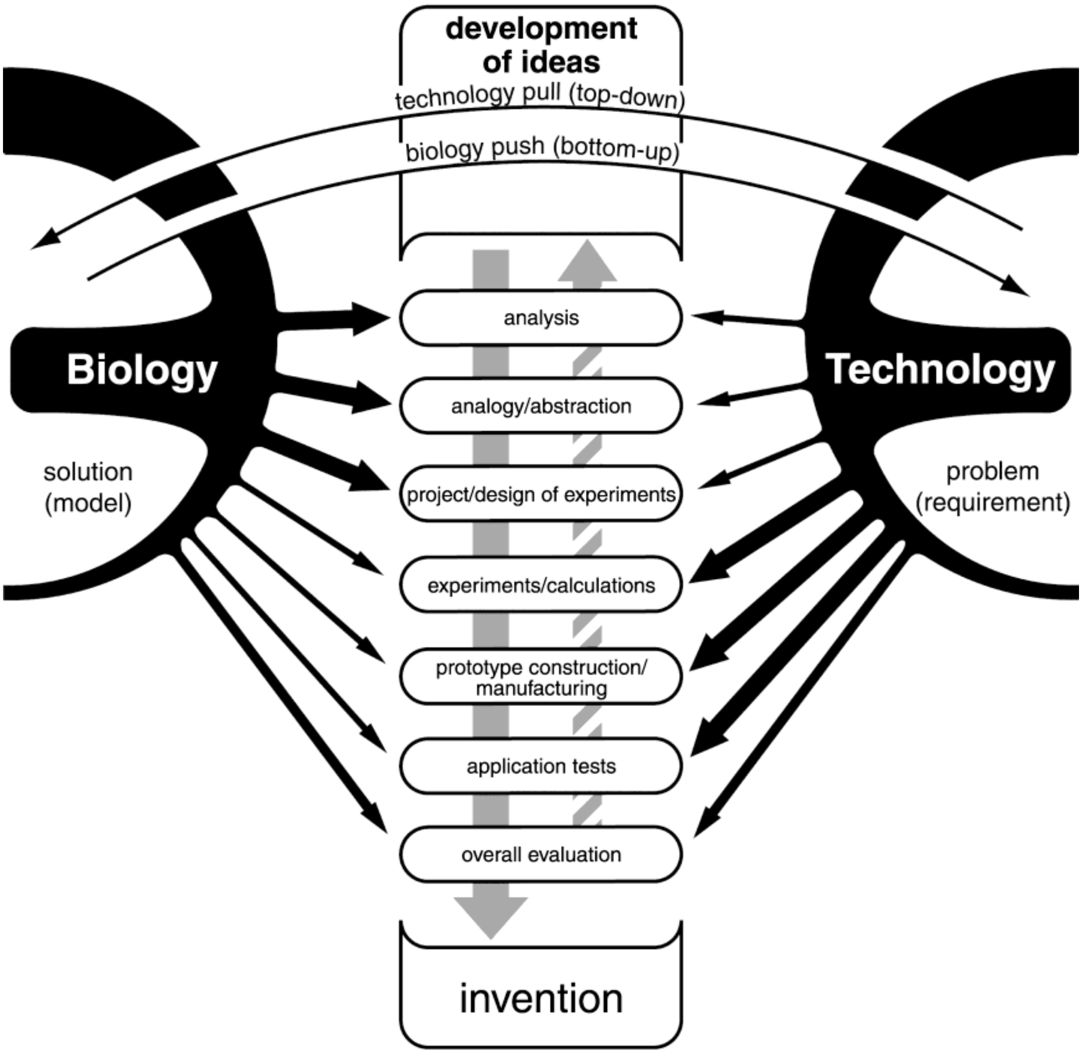

Figure 3: Schematic diagram of the development of biomimetic materials and components (push or pull) (8)

In general, bio-inspiration can be conducted either according to a so-called *solution-based* approach (Biology push) or *problem-driven* (Technology pull) (8). These two approaches (push or pull) present differences in their starting point and their design process characteristics. The solution-based approach describes the biomimetic development process in which knowledge of a biological system of interest is the starting point for technological design. This biological system performs a function with specific properties having a potential advantage if emulated in the technological field. It is necessary that the functioning of the biological system is analyzed in detail and finely understood so that the underlying principles responsible for the function identified can be extracted in order to deal with a problem or a technological field. Parallel to the *solution-based* approach, *problem-driven* approach seeks to solve a practical problem, with the starting point of its process, a problem identified belonging to the technological field. New or more efficient functions are applied by identifying a biological system performing a certain function or mechanism, then by abstracting and transferring the principles underlying the technological domain. The *problem-*

DOI: 10.13009/EUCASS2019-796

driven approach can therefore be related to a *problem-solving* approach (9). It is of importance to understand that this approach may be badly applied. An organism is found that apparently performs the same function as the one engineers are interested in (i.e. the goal is the same). But the constraints are sometimes completely different between nature and technology. Therefore, what is optimal in nature is not necessarily optimal in the technological counterpart. Also, as mentioned above, the "objective function" that nature aims to maximize is not one-dimensional (the shark skin is not only optimized for drag reduction, but also to avoid contamination). Both engineers and biologists must be aware of these differences of constraints and goals sufficiently early in the biomimetic design process.

Bio-inspiration offers a unique opportunity to provide methods, guidelines and tools that rely on more than 3.8 billion years of prior problem solving through natural selection. In many areas, living organisms still outperform our technological solutions. Biomimetic solutions are interesting, not only for their ingenuity, but also for their potential for ecological resilience. Significant research has been conducted to facilitate the systematic transfer of biological knowledge to technology, to formalize methods, to generate techniques and to create tools to facilitate the biomimetic design process (10). In recent decades, biomimetic tools have been constantly developed. An inexorable increase in the tool bank available to designers interested in the bio-inspired approach is therefore to be taken into consideration. The biomimetic toolbox is divided into three main categories: the tools from the engineering sciences, the tools from the life sciences and bio-inspired design tools, having been developed with the aim of specifically facilitating the biomimetic problem-solving approach.

However, several obstacles for the implementation of the problem-driven approach are identified in the literature (11, 12). Most of them are related to the interdisciplinary nature of this approach. Removing barriers to collaboration between engineer designers and biologists therefore seems to be a relevant lever to reduce the complexity of the implementation of the problem-driven biomimetic approach. An inherent element of bio-inspired approaches remains predominant, through the search for inspiration in the living: the search for biological models. Thus, regardless of the progress of biomimetic tools, integration of biologists within the biomimetic design cycles will remain an essential prerequisite. Far from being anecdotal, this prerequisite leads to a radical change in the way of thinking.

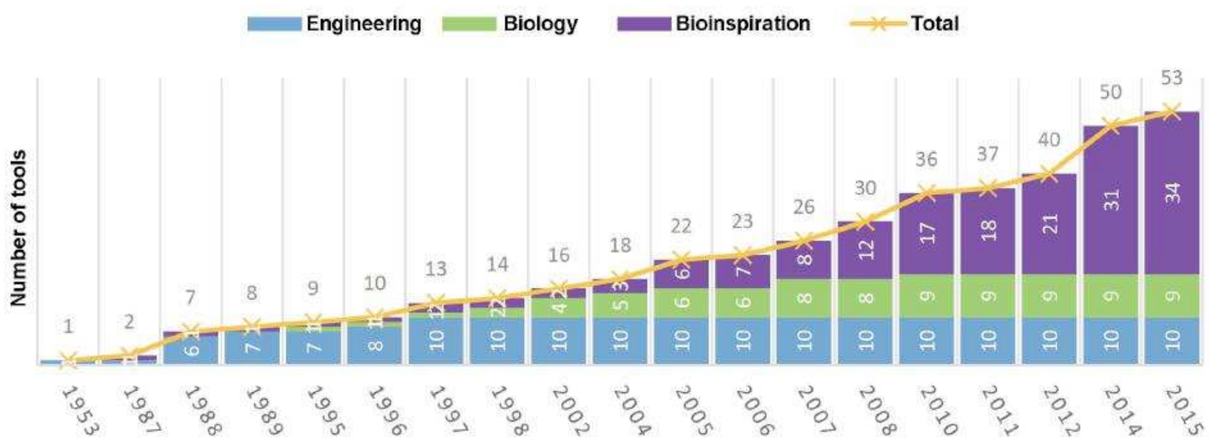

Figure 4: Appearance of biomimetic tools, classified by years (9)

4.3 Unified biomimetic model (9)

As mentioned above, a large number of biomimetic processes have been developed and are still being developed today. To simplify the biomimetic approach, most of the identified process models can be combined as a model of unified problem-driven biomimetic process presented in figure 6. This process consists of 8 steps and is not intended to be a new process model *per se*, but rather to be seen as an instrument for converging biomimetic process models. The process described in the model is subdivided into two phases, conceived as a symmetrical double cycle of abstraction-specification. The first phase (Step 1 to 4) focuses on the transition from technology to biology, while the second phase (Step 5 to 8) addresses the opposite approach from biology to technology. The field of knowledge considered at each stage is indicated by the color of marking, green for biology, blue for technology.

1. <u>*Problem analysis:*</u> this first step includes the assessment of the situation and/or the description of the problem. In the first scenario, a specific issue to consider has not been identified. The step considered then

DOI: 10.13009/EUCASS2019-796

aims to identify an axis of improvement for the technical system of interest and therefore focuses on the optimization of the system. In the second scenario, one (or many) problem(s) has already been identified. It is the description of the said problem that is a key concern. The purpose of this description is to generate appropriate formalization to avoid the complications of poorly defined problems. (Using BABELE?[1])

2. <u>*Abstraction of the technical problem:*</u> the abstraction of the technical problem leads to the obtaining of a functional model taking into account the context as well as the constraints relating to the problem; in addition, the model clarifies the function to be achieved.
3. <u>*Transposition to biology:*</u> the generation of a generic model combined with the identification of the function(s) envisaged makes it possible to transpose the problem and its environment to biology. At this stage, a question posed to nature is usually formulated. This question is intended to allow exploration of how nature has managed to achieve one or more specific functions. This third step is important because the results will be greatly impacted by the formulation of the query.
4. <u>*Identification of potential biological models:*</u> the transposition of the question makes it possible to identify biological models by research in the literature, whether the latter uses search engines or databases, or by gathering existing knowledge. Following this fourth step, a first iteration is possible. The identification of biological models can lead to a deeper understanding of the initial problem, requiring a reformulation of the problem and its biological analogy (steps 1 to 3).
5. <u>*Selection of the biological model(s) of interest:*</u> this selection step involves taking a step back from the upstream step. Once a pool of possibilities has been set up, it is necessary to put all the occurrences identified in perspective with the initial technical problem. The purpose of this comparison is to filter biological organisms according to their relevance in order to reduce their quantity to constitute a coherent workload for the rest of the process.
6. <u>*Abstraction of biological strategies:*</u> strategies implemented by biological models must be understood and abstracted. This abstraction of biological strategies is crucial, a perfect biology-technology correspondence being, in the vast majority of cases, not feasible. Generally, abstraction leads to a functional model of the biological system.
7. <u>*Transposition to technology:*</u> the transposition of biological strategies is the next step. This step builds on the previous phase of abstraction of biological strategies and usually formalizes in the form of a detailed description of the underlying principles (ex: design principles (5) or functional model (12)) of the biological system under consideration, which could then be emulated technologically.
8. <u>*Contextualization of the concept in the initial problem area:*</u> once a technological emulation process has been conceptualized, the next and final step is to implement it in the initial context and evaluate it. At this point, the cycle can be successfully completed as a result of biomimetic design. If the result does not match the design expectations, the process can either be fully re-initiated or propose an iteration of the second phase by selecting one or more new interest models.

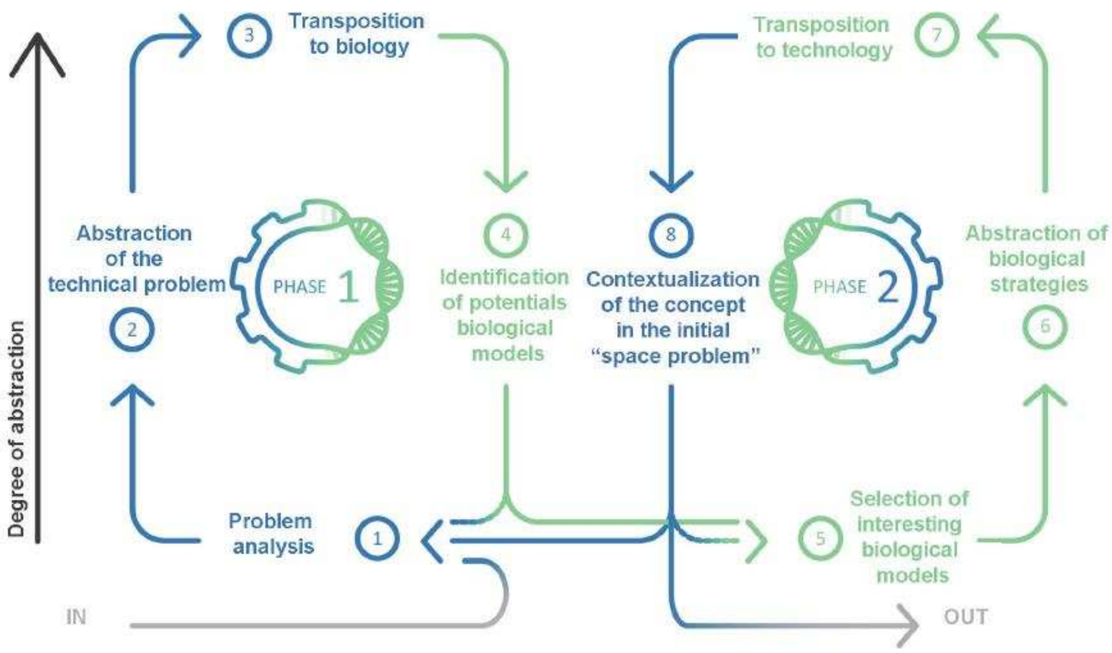

Figure 6: Unified problem-driven biomimetic process model

[1] Biomimetics Analyzer of Biologically Expertised Literature for Engineers (9)

DOI: 10.13009/EUCASS2019-796

It is said that the Shinkansen500 train used the kingfisher to improve its aerodynamics and reduce noise pollution. This led to a total reduction of the noise nuisance but also the energy needs of 15%. This bird was not the only source of innovation to solve problems related to this train. The penguins helped to improve the aerodynamics of the pantograph but especially owl feathers have inspired a way to reduce the noise nuisance of this device. Figure 7 is an illustration to better show this interdisciplinary approach model.

The problem-driven biomimetic process appears as a double cycle. This model highlights a step often left aside: the choice of the solution or the selection of the biological model(s) of interest (step 5). This step seems crucial because it is an entry point and therefore a support for the entire approach from biology to technology. The choice of an inspiration model takes into account the equivalence of biological and technological constraints and ensures the efficiency of the final product. Overall, the unified problem-driven biomimetic process model is an instrument that can help engineers and biologists to collaborate as soon as the process is established. This approach allows them to create consensus on the issues and the resources to be implemented to meet the needs. In order to make the model presented even more applicable to designers, biomimetic tools can be used to facilitate the accomplishment of each of the steps described, resulting in a potential boom in biomimetics (9).

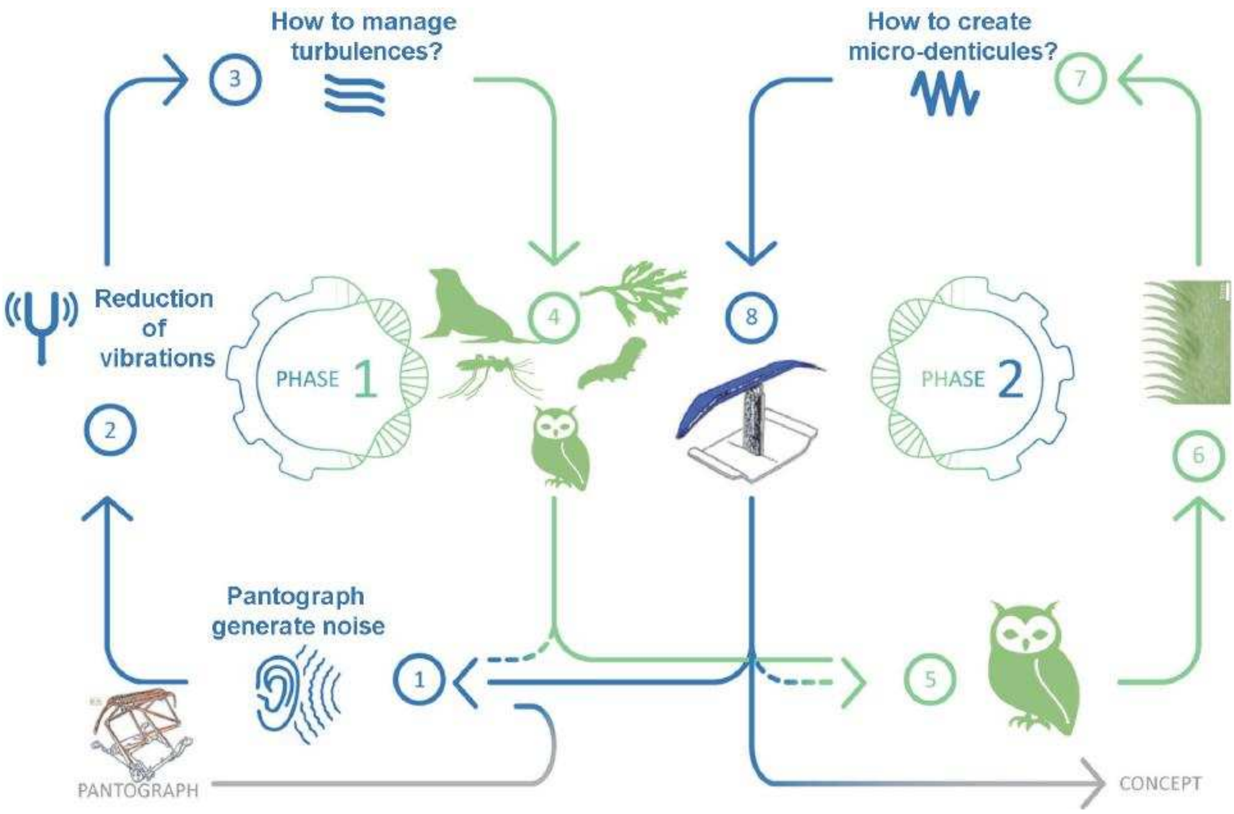

Figure 7: The unified model applied to Shinkansen500's pantograph.

Industry naturally tends to focus on engineering, but as has just been demonstrated, bio-inspiration is just as intrinsically linked to the life sciences. It is therefore important to be vigilant in maintaining a prominent place in biology within bio-inspired design approaches, while capitalizing on existing concepts and approaches within design engineering. As Buckminster Fuller famously observed, a system is greater than the sum of its part. By mixing distant fields of knowledge, **1+1=3 becomes understandable**.

5. Applications for aeronautics and space science

"Nothing is too wonderful to be true if it be consistent with the laws of Nature."
— Michael Faraday

NASA Glenn research center is currently developing an interesting platform named Virtual Interchange for Nature inspired Exploration (VINE) (13). Many other innovative departments are also already searching for nature-inspired solutions (Airbus, DARPA, MIT, etc.). Number of examples is growing. Because of a lack of place, only one application per major field of interest will be presented here that may have applications in aeronautics and space

DOI: 10.13009/EUCASS2019-796

sciences. Other examples will be simply named with the related inspiration (with concrete applications between parentheses). (2, 14, 15, 16).

5.1 Materials

Insulation materials and mushrooms (Fungus sapiens): Neither animal nor vegetable, mushroom is a kingdom on their own largely still undiscovered. Because of their ability to degrade and transform organic matter into nutrients, fungi play a central role in the environment. This decomposition is carried out, thanks to a complex system of filaments, the mycelium consisting of hyphae that secrete specialized enzymes capable of decomposing biomass-derived polymers, such as cellulose, into monomers. The material thus formed possesses properties similar to plastic and insulating polystyrene but has the advantage of being able to be manufactured under ambient conditions, without chemicals and to be entirely compostable. In addition, these kinds of materials may have interesting irradiation insulating properties that still need to be discovered. These materials could help for Long-Term Establishment (LTE). Indeed, these organisms are creating soil and many other things, but their properties are still largely underestimated.

Other examples of materials that can be of interest for aerospace industry: pressure hyper-resistant multi-layered materials: snail, oyster, abalone (MIT); insulating materials: penguin, polar bear, mushroom; intelligent materials: pinecone; porous but thermally stable materials: sponge; etc.

5.2 Surface

Drag reduction and sharkskin (Airbus): Sharks are exceptional marine predators. They can reach top speeds of 50km/h. They have a simple and sophisticated method to reduce drag. Their skin is covered with denticles, tiny scales similar to teeth, whose surface is streaked with longitudinal grooves. These microgrooves modify the flow structure of water on the skin, reducing the size of vortices generated by the displacement and thereby the resistance they generate. Scientific article has demonstrated interest with lift-to-drag ratio improvement of more than 300% (17). And, "*Airbus is considering the introduction of a sharkskin-like coating to the wings and horizontal tails of A350 XWB jetliners beginning in 2020*" (18). (N.B.: in addition, sharkskin limits fluid resistance while preventing microorganisms from growing).

Some other examples of surfaces that can be of interest for aerospace industry: self-cleaning surface: lotus leave (Lotusan); interferometric modulator display: butterfly (Mirasol); water harvesting: Namib beetle (Dar-Si-Hmad Foundation); free energy water transportation: xylem of the trees (and thorny devil lizard?); etc.

5.3 Aerodynamics

Morphing wings and birds (NASA) (19): "*NASA researchers, working in concert with the Air Force Research Laboratory (AFRL) and FlexSys Inc., of Ann Arbor, Michigan, successfully completed initial flight tests of a new morphing wing technology that has the potential to save millions of dollars annually in fuel costs, reduce airframe weight and decrease aircraft noise during takeoffs and landings. The test team at NASA's Armstrong Flight Research Center in Edwards, California, flew 22 research flights during the past six months with experimental Adaptive Compliant Trailing Edge (ACTE) flight control surfaces that offer significant improvements over conventional flaps used on existing aircraft.*"

Other examples for aerospace applications: high-speed train: kingfisher, penguins, owl (Shinkansen500); turbine blade design: harbor seal whisker, whale and dolphins (reduce drag, + applications for new kind of airships?) (20); etc.

5.4 Structure

Airless tires and honeycomb, polar bears, geckos, sea mussels, cheetah, coral, etc. (Michelin, Bridgestone, Continental, Hankook, Toyo) (21): Airless tires, non-pneumatic tires or flat-free tires are tires that are not supported by air pressure. They may be used on small vehicles but also on heavy equipment. The main advantage is that they are service free, do not go flat, they need to be replaced less and are much more resistant to load. Michelin has developed Lunar wheel for NASA moon rover vehicles (22).

Other examples: light and strong structure: water lily (Airbus); adherence and gecko; Light and functional hierarchical systems: Venus basket sponge (Gherkins tower in London); air regulation: termite mount (Eastgate center in Harare & others); choc resistant materials/auxetic materials (with negative Poisson's coefficient): Oak cork, arterial cells (Zetix); Natural alveolar structure for light and resistant materials: sponges, honeybee; etc.

5.5 Fabrication

Energy production and photosynthesis: "*Michael Grätzel created the field of molecular photovoltaics, being the first to conceive and realize mesoscopic photo-systems based on dyes as light harvesters that can rival and even exceed the performance of state of the art solar cells based on planar solid state p-n junctions. He is credited with moving the photovoltaic field beyond the principle of light absorption via diodes to the molecular level. His device presented a new paradigm since it features a 3-dimensional architecture in contrast to the planar p-n junction used in conventional solar cells. The prototype of this new photovoltaic family is the dye-sensitized solar cell (DSC), also named "Grätzel cell", which employs dye molecules, pigments or quantum dots to sensitize the mesoporous oxide semiconductor scaffold. His landmark papers published in 1985 and 1991 (J.Am.Chem.Soc.1985, 107, 2988; Nature 1991, 353, 7377) had a huge impact.*" (23)

Other potential applications: highly resistant tissue and multifunctional fibers: insect & spider fibers; low energy bacterial textile (Fungus Sapiens); radiation shields and Mycelium; breathing textiles: vegetal roots; etc.

5.6 Guidance and control

Swarm informatics and ants, barracudas, starlings (Kilobots): It's well known that ants cooperate. These tiny insects combine their efforts to accomplish complex tasks. A Mechanical Engineering team at the Georgia Institute of Technology has study why fire ants (*Solenopsis invicta*) though unable individually to stay afloat, manage to float easily when in a group (24). They observed that these ants gathered to build with their own bodies ladders, chains, walls or rafts, holding each other by their mandibles and legs. These extremely resistant structures are also impermeable, incredibly strong and self-healing. When ants collaborate, they seemingly become a super-organism.

Other potential applications: hybrid micro-electronics: bacteria; Informatics without brains: myxomycetes (*Physarum polycephalum*); sensors: black fire beetle (*Melanophila acuminata)*; biorobotic (Toro, Cheetah-cub, Robobee); etc.

5.7 System engineer

Soft robotics and octopus (PoseiDrone): The octopus is an extremely intelligent invertebrate whose tentacles show amazing dexterity. Inspired by these features, a new type of soft robot has emerged recently. The development team has developed a new technology platform encompassing flexible mobile elements, synthetic skins lined with sensors and communication protocols to control devices in networks. PoseiDRONE consists of 76% soft elastomer and weighs 0,755Kg. Its eight tentacles in silicone measure all 0,245m and its total length is 0,78m. The first prototype is able to move on uneven terrain and can grab objects with its tentacles. If the performance of this first version is currently limited, it will improve the features and strategies of the next model. (25)

These very interesting two last examples (swarm intelligence and soft robot) can lead to a new kind of bio-robot concept: eukaryotic cell (or multi-amoeba)-inspired robots. It will be a new kind of multicellular soft robots (a Mobot?). The individual soft robots will be able to fulfill several simple tasks and will also theoretically be highly resistant to radiation (because all electronic component will be inside a protective envelope surrounded with a liquid that still needs to be determined). When unicellular robot will start to work together by special links (inspired by the natural way of cells to attach to each other), they will be able to fulfill much more complex tasks. This new kind of robot may have multiple applications in space but also underwater and in high radiation zone.

Other potential applications: Schmitt's rocker (Analogic-numeric conversion): calamari; artificial intelligence: brain; intelligent ramification: tree roots; robotic exoskeleton (DARPA); memory of form; self-replication; self-assembling; broken bones electro-stimulation; etc.

DOI: 10.13009/EUCASS2019-796

5.8 *In Situ* resource utilization (ISRU) and Long-term establishment (LTE)

Biosphere2 (26): This project was an experimental system built between 1987 and 1991. The purpose of this structure was to try to recreate a viable ecosystem inside a huge closed dome. One of its objectives was to evaluate the feasibility to recreate identical biospheres than earth during spatial colonization. Although this project failed, especially concerning air recycling, this had the merit of showing the difficulty to understand and control an ecosystem. After several changes in management, the University of Arizona takes over the management of all infrastructures as a laboratory to study the effects of climate change.

Melissa's ESA (27): (Micro-Ecological LIfe Support System Alternative) is a project of the European Space Agency that aims to study autonomous systems for human food and air recycling during long-term space missions. Any long-term space mission must carry tons of consumables, which is incompatible with current logistics, hence the idea of autonomous systems to produce and recycle all these consumables. MELiSSA recovers carbon dioxide and crew waste, and forms breathable air and food from it. This is possible thanks to a set of bacteria and plants.

Uraeus0610 (28): this successful collaboration between biology and architecture is an illustration that 1+1=3. This "Science city" can be a physical and symbolical light tower of knowledge. Inspired by nature and the ancient Egyptians heritage, the project is implemented according to the Fibonacci sequence illustrated as a spiral protecting the city from the hot desiccating air of the desert. The spiral hosts a garden in its heart that spread from the core to the main entrance following a graduation of different microclimate from tropical forest to the desert. The walls structure use local materials and is inspired by the deep hydrothermal snail *Crysomallon squamiferum*. *Sphincterochila boissieri* another snail but adapted to the desert will help reduce sunshine. The inner temperature control system uses the operating principles of termite mounts (as several buildings around the world). The Venus Flower Basket sponge (*Euplectella aspergillum*) inspires the tower structure, very light and resistant (as the Gherkin building in London). An oversized system of fog-catcher nets ensures sufficient water collection for the entire system. The Namib Desert beetle (*Stenocara gracilipes)* inspires these fog-catchers. Taking inspiration from the tree xylem water evapotranspiration system and the Thorny devil lizard (*Moloch horridus)* ensures energy-free water transportation. Fourth generation photovoltaic panels (Graetzel's PV) will provide enough energy production. Wastewater management is using "Living machine systems" imitating the functioning of wetlands. All flows within the city are planned to operate circularly as an entire ecosystem where each waste becomes raw material. This science city project is fully bio-inspired and can potentially green deserts. The concepts developed in this project could easily be adapted for long-term human settlement on the moon and mars.

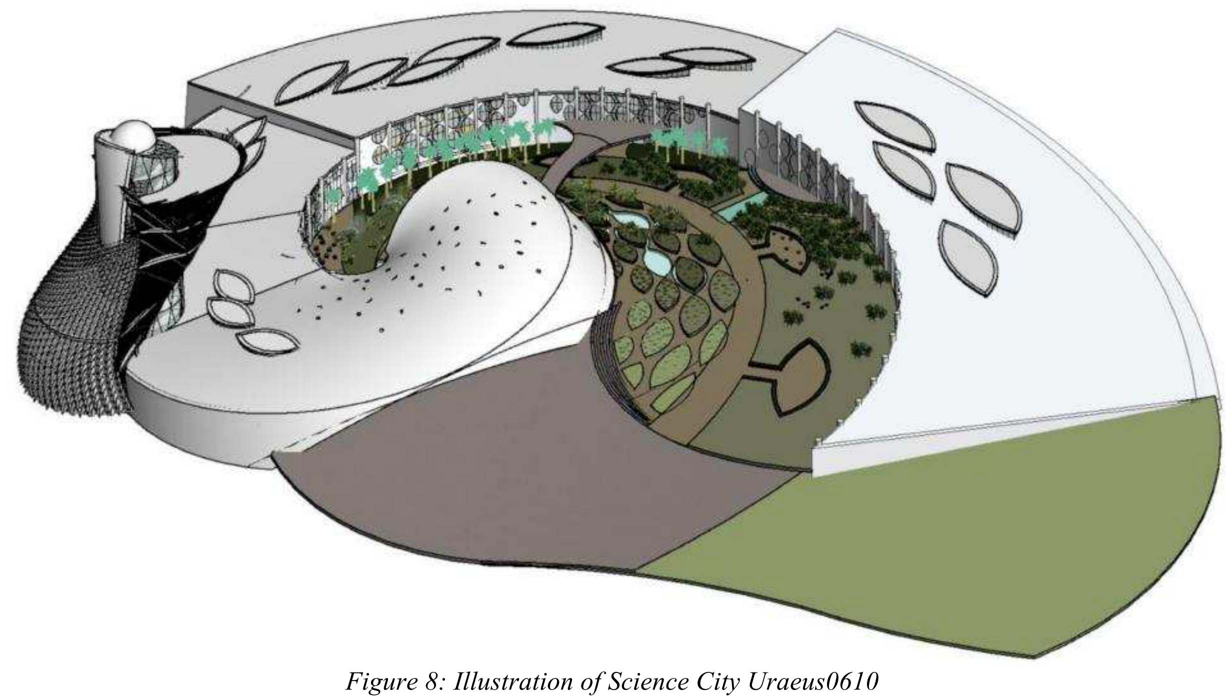

Figure 8: Illustration of Science City Uraeus0610

DOI: 10.13009/EUCASS2019-796

By 2016, European Space Agency (ESA) announced plans for building a permanent lunar base, called Moon Village[29]. Practically, this very interesting concept will consist of domes built on inflatable structures and covered with regolith thanks to swarms of robots using 3D printer technology. On the moon, the days last 15 days and the night too. This may pose a problem for energy supply if we use solar energy. A solution that has already been proposed to solve this, would be to settle in poles north or south where some places can be illuminated almost permanently, which will ensure a constant energy supply. This implies to settle near or in a crater. So the other concept that was then proposed is to stack inflatable structures in the bottom of a crater and gradually fill the rest during the stacking of these structures with regolith using 3D printer swarm robots. An elevator is even planned to pass in the stacked structures. This interesting structure will effectively protect against radiation. The problem is that putting a tube in a cone and filling the rest with regolith involves exponential (and astronomical) quantities of matter. One solution might be to use parts of the two precedent concepts and find inspiration in nature and Fibonacci. Then use the spiral design of Uraeus, this time not in 2D but in 3D. Like a snail shell structure set upside down. This will allow a habitat protected from radiation, drastically reduce the needs for materials and totally resilient because fully circularized (food, water, material). Masts will provide energy supply, even when the solar light is grazing. The construction planning will be very important because zones will have different roles depending on the time. For example, the bottom of the crater will initially serve as a habitat and then as a water reservoir (where areas may need to be planned to shelter from solar storms).

Fog&Fungi (30): As a real-life demonstration for the pertinence of the precedent project, Fog&Fungi project used only one of the innovations proposed in Uraeus0610: FogCatchers (or CloudFishers). As already mentioned, these nets are inspired by the Namid desert beetle, a beetle living in the desert able to collect water from air using tiny structure on its carapace. These nets were installed several years ago, by Dar-Si-Hmad Foundation on the heights of the anti-Atlas, a mountain-chain southern Morocco.

The fog is captured at altitude where the size of the drops is greater. The wind pushes the droplets suspended through the mesh of the net, and then slowly descends to the gutter where they form a continuous water stream. The nets have evolved since the beginning of the project. The actual technology (CloudFishers) is the latest range of Aqualonis cloud catcher. One CloudFisher Pro consists of 4 fabrics. Total net surface: 13,5m² x 4 = 54m². They are designed to withstand gusts of 120km/h and their mesh can allow a plentiful harvest approaching $55L/m^2/day$ in full fog days.

The harvesting of water is so efficient that there is surprisingly too much water. About 22 L/m^2nets/day are collected. (Data are annualized daily averages, including days of fog and days without fog). The 1686 m^2 of nets have collected about 13500 m^3/year (in 2018). The actual need for the population is 26L/person/day (average year). So, the total need is about 6730 m^3/year for 142 households of 5 persons (average). This means $6670m^3$/year excess of valuable water. Due to some residual accumulation, water can only be stored for a limited period of time and need regular flushes of 2440 m^3. These flushes unfortunately induce significant soil erosion. The average estimate provides an overall understanding of the excess water originally produced for human consumption. Excess water is likely to supply an ancillary project for consumption. This is the reason why the association sought to surround itself with landscapers in addition to scientists. This surplus could be a trigger in response to many territorial issues and used to ensure many projects using biomimetic principles for soil regeneration (permaculture, agroforestry, etc.). Dar-Si-Hmad Foundation thus enabled a collaboration with French students of superior national school of landscape of Versailles-Marseille, Fungus Sapiens and the European school of Ecological Transition.

The Argan tree (*Argania spinosa*), a living tree in this region of the world, inspires this ongoing project. The upper part of this tree is covered with moss able to capture water (like fog-catchers). Argan trees have root system necessarily associated with mushrooms that increase the surface of capture, *mycorhizae*. These mushrooms are of crucial importance for the creation of soils. Indeed, Fungi have the ability to create soil from almost nothing thanks to specialized enzymes produced by these organisms. By creating soil, fungi (in association with bacteria) enable plants and animals to colonize land. This kind of model could be multiplied and scientifically followed to improve our understanding of eco-systemic regeneration on our planet. This will improve resilience of our cities and also greatly facilitate the long-term establishment of humanity on other planets of our solar system (as "backup").

Other interesting projects: Eden project; Sahara Forest Project; Biospheric project; Transition town network; Permaculture network; Ceinture Aliment-Terre Liege; Ecotopia; Water For All projects with Apollo 1, 2 &3; etc.

DOI: 10.13009/EUCASS2019-796

6. Conclusion

"We cannot solve our problems with the same thinking we used when we created them"
A. Einstein

Access to cheap energy fuelled the industrial revolution, which has had dramatic consequences on our environment. Engineers, architects, designers are solving problems everyday most of the time unaware that there are plenty of solutions just around them. With about 4 billion years of R&D, nature is full of knowledge that biologists (and also paleontologists and others) are trying to decipher these whispered secrets. To get the best out to of this knowledge, it is important to induce a paradigm shift and establish real interdisciplinary collaborations. We all have much to learn from others and many tools already exist to help communication between fields sometimes quite opposite.

Hopefully, examples of biomimetic solutions are more and more numerous. However, the lessons of the time must make us realize that nature is infinitely more powerful than all our technical solutions. Technology will not be enough in front of the tremendous modifications that are coming. We also need to become more humble and start to see what lessons nature can give us. The huge challenge humankind is actually facing may help ecological transition where we are going to reconcile with nature. Indeed, the human being is inherently biophilic: being disconnected from our own nature often induces mental illnesses that can, most of the time, disappear by simply being more in contact with life (gardening, barefoot walking on the grass or in the woods). This urgent actually needed paradigm shift to accelerate ecological transition is about survival of humankind: not only to regenerate our planet but also to build "backups" away. Even if some cataclysmic event eradicates humanity, our planet and life on it will survive. We are only a very young species. But, we are adaptable and smart. Let's hope we will be smart enough and be able to shift from ego to eco.

7. References:

"An experiment is a question which Science poses to Nature
and a measurement is the recording of Nature's answer."
— Max Planck

(2) Emilie J. Siochi, John B. Anders, Jr., David E. Cox, Dawn C. Jegley, Robert L. Fox, and Stephen J. Katzberg. *Biomimetics for NASA Langley Research Center - Year 2000 Report of Findings From a Six-Month Survey*. Langley Research Center, Hampton, Virginia. Feb 2002

(3) Steffen et al. 2015. *Planetary Boundaries: Guiding human development on a changing planet.* Science Vol. 347 no. 6223. Which is an update of Rockström J., Steffen W., Noone K., Persson Å., Stuart Chapin III F., Lambin E.F., Lenton T.M., Scheffer M., Folke C., Schellnhuber H.J., Nykvist B., de Wit C.A., Hughes T., van der Leeuw S., Rodhe H., Sörlin S., Snyder P.K., Costanza R., Svedin U., Falkenmark M., Karlberg L., Corell R.W., Fabry V.J., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P. & Foley J.A. Sept 2009. *A safe operating space for humanity.* Nature 461, pp472-475. And also, Rockstorm et al. 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 14(2): 32.

(4) Dunlop I. & Spratt D. June 2017. *Disaster alley – Climate change conflict & risk.* Breakthrough National centre for climate restoration.

(5) Baumeister D., Tocke R., Dwyer J., Ritter S. & Benyus J. 2013. *Biomimicry ressource handbook – A seedbank of best practices*.

(6) Hoagland M.B., Dodson B., Hauck J. 2001. "*Exploring the Way Life Works: The Science of Biology"*.

(7) Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., and Pahl, A.-K. 2006. *Biomimetics: its practice and theory*". Journal of the Royal Society Interface, vol. 3, pp. 471-482,

(8) ISO/TC266. 2015. *Biomimetics - Terminology, concepts and methodology.* ISO 18458:2015. Ed: Beuth Verlag.

(9) Fayemi P.E. 2016. *Innovation par la conception bio-inspirée : proposition d'un modèle structurant les méthodes biomimétiques et formalisation d'un outil de transfert de connaissances*. Génie mécanique [physics.class-ph]. Ecole nationale supérieure d'arts et métiers - ENSAM.

(10) Nagel J.K., Nagel R.L., Stone R.B., and McAdams, D.A. 2010. *Function-based, biologically inspired concept generation*. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, vol. 24, pp. 521-535.

(11) Yen J., Helms M., Goel A., Tovey C. and Weissburg M. 2014. *Adaptive evolution of teaching practices in biologically inspired design*. in Biologically Inspired Design , ed: Springer, pp. 153-199.
(12) Helms M., Vattam S.S. and Goel A.K. 2009. *Biologically inspired design: process and products*. Design studies, vol. 30, pp. 606-622.
(13) www.grc.nasa.gov/vine/ (Retrieved June 16th 2019)
(14) Kapseli V. 2016. *Biomimetics for designers. Applying nature's processes & materials in the real world*. Thames & Hudson Ltd.
(15) Ternaux E., Gomez B., Kula B., Ternaux M., Ternaux J.P. 2012. *Industry of Nature. Another approach to ecology.* Frame Publisher.
(16) www.asknature.org (Retrieved June 15th 2019)
(17) August G. Domel , Mehdi Saadat , James C. Weaver, Hossein Haj-Hariri , Katia Bertoldi and George V. Lauder. 2018. *Shark skin-inspired designs that improve aerodynamic performance.* Journal of the Royal Society interface.
(18) www.airbus.com/newsroom/news/en/2018/01/biomimicry--engineering-in-nature-s-style (Retrieved June 15th 2019)
(19) NASA Successfully Tests Shape-Changing Wing for Next Generation Aviation. www.nasa.gov/press-release/ nasa-successfully-tests-shape-changing-wing-for-next-generation-aviation (Retrieved June 16th 2019)
(20) Shyam V., Ameri A., Poinsatte P., Thurman D., Wroblewski A. & Snyder C. 2015. *Application of Pinniped Vibrissae to Aeropropulsion*. ASME Turbo Expo: Power for Land, Sea, and Air, 2A: V02AT38A023.
(21) Tire technology international. 2017 from: www.uakron.edu/cpspe/documents/TireTech+Hannover+ 2018.pdf (Retrieved June 16th 2019)
(22) Fazelpour M. & Summers J.D. *Evolution of meso-structures for non-pneumatic tire development: a case study.* Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE August 17-20, 2014, Buffalo, New York, USA
(23) www.epfl.ch/labs/lpi/graetzel/ (Retrieved June 16th 2019)
(24) Phonekeo S., Mlot N., Monaenkova D., Hu D.L. and Tovey C. 2017. Fire ants perpetually rebuild sinking towers. R Soc Open Sci.; 4(7): 170475.
(25) sssa.biороboticsinstitute.it/projects/PoseiDRONE (Retrieved June 16th 2019)
(26) biosphere2.org (Retrieved June 16th 2019)
(27) www.melissafoundation.org (Retrieved June 16th 2019)
(28) Finzinger C., Luxen J. & Hoornaert S.G. 2017. *Uraeus0610 – A Science City to green the Sahara desert.*
(29) www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village (Retrieved June 18th 2019)
(30) Lampe T., De Saint Just C., Peñalva M. & Hoornaert S.G. 2018. *Fog&Fungi : Projet d'oasis aux portes du Sahara.* Ecole nationale supérieure du paysage Versailles Marseille; Dar Si Hmad; Fungus Sapiens; Ecole Européenne de la Transition Ecologique (ETRE).

Interesting TED:

- Janine Benyus: Biomimicry's surprising lessons from nature's engineers
- Michael Pawlyn: Using nature's genius in architecture
- Regina Dugan: From mach-20 glider to hummingbird drone
- Paul Stamets: 6 ways mushrooms can save the world
- Etc.

Acknowledgments to Abbes B., Caroline Z., Christophe d., Dayna B., Janine B., Gauthier C., Greta T., Jamila B., Julian V., Kalina R., Keiko H., Michael P., Naoe H., Norbert H., Paul S., Pascal R., Pierre Emmanuel F., Rob H., Titouan L., Tristan G., Veronika K., and of course Jacqueline B. & Jean-Claude H., (+ many others) for who you are, what you do and what you inspire. ;)