Introduction to

NATURE INSPIRED SOLUTIONS

A guide to entrepreneurs and innovation support organizations to implement Biomimicry as a tool for responsible innovation

PARIS REGION ENTREPRISES

karim
knowledge acceleration responsible innovation meta network

INTERREG IV B - 207G - KARIM
KARIM Project is co-financed by the European Union.

European Union
European Regional Development Fund

Investing in Opportunities
This project has received European Regional Development Funding through INTERREG IV B.
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This manual has also benefited from discussions with several entities involved in the promotion of nature inspired solutions to address societal challenges. We would especially like to thank the CEEBIOS (European Biomimicry Center of Excellence of Senlis), Institut Inspire, Active Innovation Management, Biomimicry Germany and Bayonik for their inputs.

Edition - January 2015

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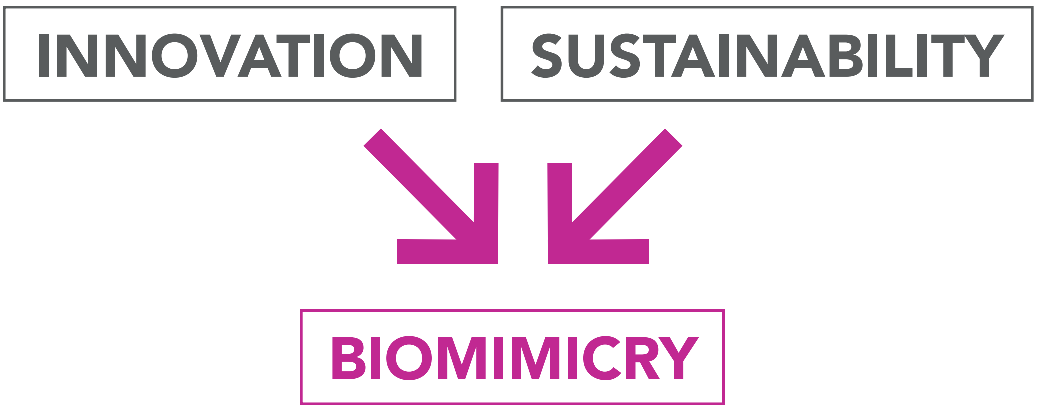
Introduction

The present manual is both an introduction to the emerging concept of biomimicry (bio=life, mimesis = imitate) and a guide for considering such an approach as a responsible innovation opportunity within a project. It is thus a complement to the KARIM Responsible Innovation manual.

This guide is aimed both at innovation support organizations and entrepreneurs, in order to:
- raise awareness about the potential of nature inspired solutions for responsible innovation
- propose ways to improve the product (especially in terms of sustainability), by taking inspiration from living systems

Over 3.8 billion years of evolution, living systems have been optimized regarding matter, energy and information flows. Through that optimization process, natural selection has sorted out the most sustainable systems in terms of energy and water management, eco-materials production, information processing as well as organization and collective intelligence efficiency.
Human societies are evolving living systems subjected to the same environmental constraints and physical laws (planetary boundaries, biochemical cycles, geological cycles…) as non-human living systems. Understanding and mimicking living systems properties is thus a relevant frame to engage into responsible innovation.
As an introductory tool, this guide is focused on the analysis of **material systems** and doesn't address organizational or management issues, because aspects related to the material system are by themselves already complex and rich in opportunities.



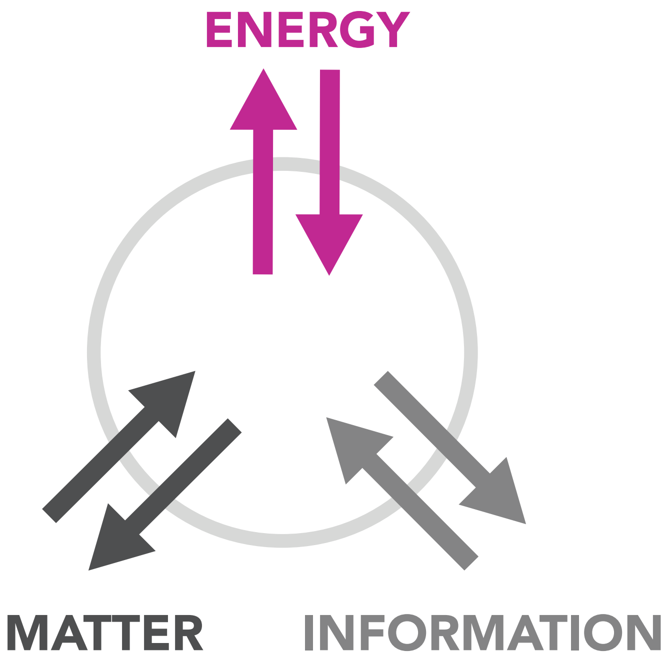
Framework for Responsible Innovation

Biomimicry:

nature inspired solutions

Traditional product or service design and innovation usually consists either in improving existing ones in terms of resource consumption, waste management, and impact on the environment, or trying to imitate natural materials using standard methods. Because human societies are by themselves living systems, constrained by the Earth's physical and biological boundaries, new industrial innovations and processes may be achieved by learning from living species and ecosystems.

Living systems, from cells to ecosystems, are open self-organizing systems, in interaction with their environment. These systems rely on three flows: matter, energy and information.



Living systems have the capacity to arise through a circular process in which they « self-produce » their own components: feedback loops are used to make the necessary changes in order to survive, grow or reproduce. The peculiarity of any open system (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.

At the species level, natural selection, over 3.8 billion years, has constrained organisms to solve the challenges of feeding, locomotion, and reproduction in ecological systems that are able to sustain themselves in dynamic environments. Evolution has thus selected the most adapted and adaptable systems, which are optimized regarding energy, matter and information management.

LEARNING FROM EVOLUTION

There are three main strands of bioinspiration:

1. **Learning from the results of evolution (i.e mainly recording and understanding form / function relationships);**

2. **Learning from the processes of evolution (i.e morphogenetic algorithms and genetic variation, coevolution, etc...);**

3. **Learning from the successfull strategies resulting from evolution based on the abstraction of the admittedly and generalizable principles of evolutionary success (solar energy, water based, ambient pressure, hierarchical structuring, etc...).**

Since the first strand depends on the specificities of the selected living system as a model to be analysed, this manual will especially focus on underlying principles in line with the second and third strand.

3,8 Billion Years, 10 Million Species

RECYCLE/PURIFY
PRODUCE ENERGY
SYNTHESIZE/DECOMPOSE
R&D
MANAGE INFORMATION
EXCHANGE/COLLABORATE
RESIST AGGRESSIONS
PERFORMANT MATERIALS
DISTRIBUTE/STORE
MOVING/ADHERE

LOCAL AND ABUNDANT RESSOURCES
COOPERATION
MODERATE TEMPERATURE AND PRESSURE
ZERO WASTE
ADAPTATION
SOLAR ENERGY
BIOCOMPATIBLE OR BIO-DEGRADABLE MATERIALS
RESILIENCE
ENZYMATIC AND CATALYTIC CHEMISTRY

Overview of some functions and strategies of living systems

In many fields, living organisms and ecosystems outperform man-made solutions. Biomimetic solutions are thus widely regarded as not only being ingenious, but also being ecologically sound, resilient, and low-risk.

Biomimicry is an original approach to conciliate both the need for disruptive innovation, looking through a library with 10 million species examples, and sustainability issues by learning from 3.8 billion years of evolution. It thus meets the opportunities of responsible innovation as described in the KARIM Responsible Innovation Manual.

Going beyond mere imitation, biomimicry consists of seeking a form of emulation in order to reproduce a living process and to adapt this solution to its new context. Biomimicry thus aims to find functional analogies in the living world, abstract biological design strategies, and transfer them for human innovation[1].

Implementing a bio-process, or exploiting the product of a living organism, does not amount to emulation and cannot be considered as biomimicry, unless the use of this process participates to an organisationally inspired approach (myco-remediation, phyto-remediation, agro-forestry, white chemistry…).

Nature-inspired solutions can lead to sustainable innovation, but we should also add the contribution of biomimicry to the goal of maintaining biodiversity, as bio-inspired innovations demonstrate the cultural (knowledge) and economic importance of biodiversity.

However, bio-inspiration does not lead to systematic sustainable solutions. Indeed, bio-inspired products could be manufactured using materials that are neither environmentally compatible nor meet the requirements for sustainable production and products. **To be sustainable, a bio-inspired innovation should integrate all dimensions of Biomimicry: product design, production, use and end-of-use should employ renewable energy and material resources, no persistent toxics or harmful waste generation, and within a network of relationships with other systems (life cycle).**

[1] According to that framework, aesthetic inspiration does not fit to the Biomimicry definition

Biomimicry opportunities for entrepreneurs

The primary intention of this guide is to identify paths of improvement in innovation processes by looking at successful strategies optimised by living systems.

This guide is organized organized in three main sections:

MIMICKING LIVING SYSTEMS PROPERTIES.

This first section covers those properties that allow for optimised performance of products. These properties, arising from matter, energy and information flow optimization, can be seen as 'design rules' for successful products that are not only more ecological but also more performant. 10 design principles are listed.

SOLVING SPECIFIC TECHNICAL CHALLENGES.

If specific technical challenge can be sufficiently well defined, then a direct 'search' in the large library of nature can reveal applicable solutions inspired by an individual organism. This third part introduces a 4 step methodology to tackle such specific technical challenges.

MIMICKING LIVING SYSTEMS MATTER, ENERGY AND INFORMATION FLOW OPTIMIZATION.

As no single product stands isolated from its environment, these principles concern the way its primary materials are sourced, fabricated, used and re-used/recycled. Integrating the principles for optimised flow of matter, energy and information goes towards a circular approach in which there is no waste and a product can even have a net positive impact on its environment through its entire life cycle.

You can read this guide in any order, starting from one of these three sections according to your own primary interest: living system properties (section 1), practical implementation with flow optimization (section 2), methodology (section 3)

For these two sections, several design principles are listed. These principles emerge from observable performance level carried out on living organisms, revealing interesting traits regarding sustainability issues.

For each principle, you will find:

- a DESIGN PRINCIPLE section, defining the principle
- an ADVANTAGES section, highlighting the potential of the design principle
- BIOLOGICAL EXAMPLES
- TECHNICAL EXAMPLES of products fulfilling the principle
- SAMPLE QUESTIONS to the entrepreneur or the advisor about the product

Note that **living systems fulfil all these principles**. The reader can thus use that guide as a checklist of criteria, necessary to reach responsible innovation specifications within a project.

This part introduces the methodology to extract and abstract knowledge from biology in order to solve singular technical challenges.

LIVING SYSTEMS PROPERTIES

P1. (Self-)assembly
P2. Modular
P3. Resilient
P4. Multifunctional
P5. Adaptable
P6. Evolving
P7. Learning
P8. Form adapted to function
P9. (Self-) reparable
P10. Disassembly

LIVING SYSTEMS MATTER, ENERGY AND INFORMATION FLOWS OPTIMIZATION

O1. Renewable resources
O2. Recyclable and recycled materials
O3. Locally available
O4. Non fossil sourcing
O5. Mutualized
O6. Local Export
O7. Compatible with the living
O8. Green chemistry
- O8.1. Operation under mild conditions
- O8.2. Water as solvent
- O8.3. Abundant atomic elements
- O8.4. Enzyme catalysis

O9. Additive manufacturing
O10. Biodegradable
O11. Energy provider
O12. Diversity of storage and distribution strategies

SOLVING A SPECIFIC TECHNICAL CHALLENGE

Step 1: Functional definition of the challenge
Step 2: Find biological solutions to that functional challenge
Step 3: Abstract and emulate into human technologies or systems
Step 4: Check for sustainability

Design Principles and Methodology

P1. Self assembly

DESIGN PRINCIPLE

Design the product so as to simplify the process of assembly to the maximum while reducing the energy and material costs of the operation.

ADVANTAGES

Self-assembly offers the advantage of lightening the production process. Investment in an assembly line and its maintenance is no longer necessary, thus mitigating material and energy costs associated with producing the product.

SAMPLE QUESTIONS

- What steps consume most of the resources and time in my assembly process?
- Can I remove or modify them?
- What is it, in the design of the components relating to this stage, that requires such an assembly process?
- Can I rethink my components so as to limit the complexity of the assembly?

BIOLOGICAL EXAMPLES

- Living systems in very large part rely on self-assembly, constructing themselves starting from materials and energy available in the environment, and based on the information contained in their genetic material.

TECHNICAL EXAMPLES

- Self-assembling technical systems are still rare but interesting advances have been made in the development of nanomaterials. A wide range of research is also presently working on self-assembling structures based on macromolecules issuing from living ones, such as DNA and RNA.

P2. Modular

DESIGN PRINCIPLE

Design the product so that the greatest possible number of its components function independently from their belonging to a given system.

ADVANTAGES

Modular components reinforce the robustness and capacity for evolution of the product, since they can easily be removed from it and replaced. The life span of a product can thus be increased, with associated economies in energy and materials.
Modular components can be functional across several types of products, thus reducing the design effort required.
Lastly, after disassembly of a product at the end of its life span, those components that are still functional may then be reintegrated into other products, of the same or a different type, thus providing economies in energy and materials.

SAMPLE QUESTIONS

- Which components are only functional in the context of my product?
- Why are they not functional outside it?
- Can I rethink them so that they function independently from their belonging to the product?

BIOLOGICAL EXAMPLES

- Living organisms are constructed of modular units that are coherent within themselves and yet part of a larger unit. Thus, cells are parts of tissues, which are parts of organs, which are parts of systems, and so on. Such a hierarchically nested system allows certain parts of the body to change without interfering with the functions of other parts. This principle of modularity allows fundamental biological processes as association, dissociation, duplication and divergence.

TECHNICAL EXAMPLES

- Electronic systems, while not directly bio-inspired, are a fine example of a modular technical system. The resistors, capacitors and various diodes are built according to defined standards, and can be removed from their initial circuits and be later reintegrated into other circuits.
- Other examples:

  The OpenStructures system of object, relies on a standard grid of fixed dimensions, permitting the assembly of components from different products designed on the basis of this grid. At the end of their life, the products can be disassembled, and the still functional components re-used in new products, either of the same or of a different type.

  Interface Floor and its carpet tiles.
- A counter-example of modular components is, for example, car bumpers. These are generally designed in relation to a specific model of car, and have no utility once removed from their context (i.e., that particular model).

P3. Resilient

DESIGN PRINCIPLE

Product's essential functions are decentralised and carried out by diversified and redundant sub-systems.

ADVANTAGES

The resilience of a product increases its life span, and thus produces economies in both energy and materials.

SAMPLE QUESTIONS

- Which of my essential functions are not decentralised or could be carried out by diversified and redundant sub-systems?
- Why aren't they decentralised?
- Why aren't they carried out by diversified sub-systems?
- Why aren't they carried out by redundant sub-systems?
- Did I think about a specific design increasing the resilience of my network of relationships among the components of my system? Especially if information flows are involved?

BIOLOGICAL EXAMPLES

- Living systems are distinguished by their resilience relying on their ability to maintain, or at least recover complete functionality after a disruption or partial destruction. This relies on three properties: decentralization, diversity of species and redundancy. For example, in a mature ecosystem, living matter decomposition is distributed over a large range of species (fungi, bacteria, insects…).

TECHNICAL EXAMPLES

- Certain essential systems on aircraft exist in several types, located at different places in the craft, and operate on the basis of diversified (mechanical, electronic, pneumatic) solutions.

P4. Multifonctional

DESIGN PRINCIPLE

The product possesses several essential functions.

ADVANTAGES

The fact that a product has several functions renders the system more efficient per unit and in energy consumption. It also facilitates the emergence of redundancy and the decentralisation of a function across a small number of systems; this is interesting from the point of view of resilience.

SAMPLE QUESTIONS

- What are the key functions my product necessitates to deliver desirable outputs?
- Are there components or subsystems that could be re-designed to deliver several functions at once?

BIOLOGICAL EXAMPLES

- A very large part of living systems are multifunctional.
- For example, a tree stores CO2, it protects against soil erosion and drying out, produces leaves, seeds and edible fruit for several species, and serves as a habitat for other wildlife, etc.
- In the same way, the carapace material of insects has multiple functions: structure, colour, protection, reproduction, gas exchange, etc.

TECHNICAL EXAMPLES

- Some of technical systems are multifunctional. A flagrant example is the smartphone, which integrates several features as phone, compass, GPS positioning, camera and a multitude of other functionalities thanks to applications based on the network of sensors integrated into the product. However, there are not eco-conceived. The PhoneBlocks and FairPhone alternatives, pave the way to more responsible smartphones.
- The Paris region SMEs, X-Tu has developed photo-bio reactors that purify waste water, while capturing CO2 in the building and producing energy from microscopic algae.

P5. Adaptable

DESIGN PRINCIPLE

The product can modify its state or its behaviour in relation to its own state or the state of its environment.

ADVANTAGES

The adaptability of the system to ambient conditions is powerful from an economic point of view and saves resources. By triggering the mechanism solely in a given situation, the consumption of energy and materials can be drastically reduced. In the case of a multifunctional object, the product can even activate a specific function only when it is suitable and in a given situation.

SAMPLE QUESTIONS

- Is it interesting in terms of energy or material efficiency, to multiply the states and behaviours of my product? (a simple example: active and standby modes).
- On which environmental variables could we base a change of state or behaviour signal?
- Can I rethink my product in order to multiply its states and behaviours?
- Can I rethink my product in order to render it sensitive to variables pertinent to its state and that of its environment?
- Can I add a system to my product that determines its state or its behaviour in relation to pertinent environmental variables?

BIOLOGICAL EXAMPLES

> One of the great strengths of living systems is their adaptability. There are innumerable regulation mechanisms in living species, often highly efficient.

> Certain bacteria are capable, when resources are rare, of sporulation. They produce an extremely reduced form of their cells capable of resisting prolonged periods of dearth and extreme environmental conditions. Once the situation improves, they can easily redevelop a fully functional cell from the sporular form.

TECHNICAL EXAMPLES

> So called 'intelligent' technical systems also possess regulation mechanisms, such as the thermostat of a radiator which allows heating a space solely when the ambient temperature reaches a given threshold.

P6. Evolving

DESIGN PRINCIPLE

Product's structure can evolve as a function of its state, or that of its environment.

ADVANTAGES

An evolving product with the ability to change its intrinsic structure is even more robust than a resilient or adaptive object. Its life span can potentially be even longer, which improves both its energy and material efficiency.

SAMPLE QUESTIONS

- Can I rethink my product in order to make it apt to modify its own structure?
- Can I add a system to my product that will allow it to change its own structure, depending on its state or that of its environment?
- Can I model the environmental constraints of my product and use evolutionary algorithms?

BIOLOGICAL EXAMPLES

- The Biosphere as a system is evolving via mutations due to various environmental factors.
- At the scale of organisms, some of them can modify the information of their genetic inheritance via genetic mechanisms, in order to structurally evolve in relation to the environmental conditions.

TECHNICAL EXAMPLES

- Many nursery items are designed in order to be reshaped depending on child's development.
- Evolutionary algorithms, use mechanisms inspired by biological evolution, such as reproduction, mutation, recombination, and selection. They have shown successes in fields as diverse as engineering, art, biology, economics, marketing, genetics, operations research, robotics, social sciences, physics, politics and chemistry.

P7. Learning

DESIGN PRINCIPLE

Product is capable of modifying and reinforcing existing knowledge, behaviors, skills and preferences and is able to process different types of information.

ADVANTAGES

The presence of a memory and the ability to positively or negatively evaluate an experience is interesting in order to increase efficiency and speed. The product can thus recognise a similar already experienced situation, and directly trigger an optimised solution in response.

SAMPLE QUESTIONS

- How can the product use memory in order to increase its energy and material efficiency?
- What are the important internal and external variables to measure and memorise?
- Can I rethink my product in order to integrate a form of memory that will influence behavioural / functional responses?

BIOLOGICAL EXAMPLES

- Numerous animals, including humans, have both memory and the ability to positively or negatively evaluate an experience.

TECHNICAL EXAMPLES

- Some software products and robots, some of them bio-inspired, are beginning to benefit from such abilities.

P8. Fitting form to function

DESIGN PRINCIPLE

Design the shape of at least one of the components of the product in order to reduce the quantity of materials and/or energy used by a functional unit across its life cycle.

ADVANTAGES

A finely designed shape sometimes avoids having to resort to more complex systems that consume more energy and materials.

SAMPLE QUESTIONS

- Are all the shapes of the components of my product clearly linked to desired functions and outputs?
- Can I rethink the shape of one of my components in order to reduce consumption of materials or energy?
- Can I reduce the complexity of a component by rethinking its shape?

BIOLOGICAL EXAMPLES

- All the way down to nanometre sized components, living species have optimised shapes that reduce the complexity of the systems concerned while increasing their efficiency in terms of energy and materials. For example, the beak of a kingfisher allows the bird to plunge into water as rapidly as possible with a minimum of turbulence, thus gaining precious fractions of a second with which to seize its prey.

TECHNICAL EXAMPLES

- The shape of a Kingfisher's beak served as an inspiration during the design of the Shinkansen, the Japanese high speed train. This locomotive crosses dense urban conglomerations and enters numerous tunnels, the shock waves generated by the high speed train entering tunnels posed problems both in energy consumption and noise pollution. The use of its bio-inspired shape has significantly reduced sound levels and energy consumption.

P9. (Self)-repairable

DESIGN PRINCIPLE

Design a product in order to minimize its number of critical components, i.e., components whose end of life forces the entire product to end of its life span.
AND
The repair service and spare parts procurement are designed in parallel with the product.

ADVANTAGES

Self-repair increases the life span of a product without having to manage its end of life cycle and its concomitant new production phase. This represents important savings in materials and energy.

In the case of a repairable product, rather than self-repairable, the repair service and the purchase of spare parts must be designed in parallel with the product, otherwise the design efforts will be in vain in terms of its advantages.

The repairability of a product only makes sense if a functional repair and maintenance service is provided. In cases where it is impossible for consumers to repair a dysfunctional product, despite the design effort made in this direction, the product risks being discarded and the effort becoming meaningless.

SAMPLE QUESTIONS

- Which are the critical components of my product?
- How can I rethink my product in order to eliminate these critical characteristics?
- How can I make my product easily repairable during its phase of use (repair and maintenance service, spare parts procurement, Internet FAQ and/or forum...)?

BIOLOGICAL EXAMPLES

- Our skin is capable, on being broken, of healing. Our liver likewise possesses a considerable ability to regenerate itself.
- Rhinoceros horn, constantly repairs any micro-fractures. Our bones are also capable of regenerating themselves and healing after fracture.

TECHNICAL EXAMPLES

- Several self-repairability products have been developed. A platelet system developed by Brinker Technologies was inspired by the coagulation system present in the blood circulation system. Its aim is to repair leaks, for example in oil pipelines. A cement incorporating micro-capsules of resin that can repair potential cracks has also been developed. Self-repairing membranes for Tensairity® inflatable structures have also been developed.

P10. Disassembly

DESIGN PRINCIPLE

Design the product so as to facilitate its disassembly at the end of its life cycle.
AND
The collection and disassembly channel for the product at the end of its life cycle was designed and set up in parallel with the design of my product. Ideally, the product is disassembled at the end of its life span by other self-assembling products.
AND
Non functional components are disassembled into essential functional components, which can then be re-assembled.

ADVANTAGES

A disassembled product permits the separation of functional components from non functional components at the end of its life. A functional component will be reintegrated into new products. The non functional components will be recycled. This permits important savings in raw materials and energy, by limiting recourse to the use of raw materials, and by limiting the number of new components needing to be produced for new products.

The advantage in terms of sustainability regarding a disassembled product, i.e. the recovery of the components, is entirely dependent on appropriate infrastructure and a channel under the control of the enterprise. Thus, the channels collecting such products at the end of their life cycle and the disassembly process must be designed in parallel with the product for these advantages to be enjoyed.

The savings in materials and energy implied by such an imbrication of the life cycles of two products can be very large. The autonomous character of the process can equally prove very interesting.

Designing a product at the level of an interlocked complexity of its functional components greatly facilitates re-use. In fact, if a malfunctioning component is disassembled into functional components of a lower level of complexity, these components can then be re-injected into the production process in order to produce new products, thus avoiding recourse to material and energy resources as yet unexploited.

SAMPLE QUESTIONS

- Which steps in the disassembly process consume the most resources and time?
- Why are they so problematic?
- How can I rethink my product so as to simplify its disassembly?
- How to organise the collection of my products at the end of their life cycle?
- How to test whether components taken from my product are still functional?
- How to reintegrate these still functional components into the production process?

BIOLOGICAL EXAMPLES

- The majority of living organisms are decomposed at the end of their life by other organisms, decomposers that are capable of degrading organic molecules into bio digestible nutriments. This is the role of a large part of our intestinal flora.
- Proteins are made up of amino acids assembled into long chains. When a protein is degraded, and is no longer functional, the organism breaks it down into amino acids which are then re-assembled into new proteins.

TECHNICAL EXAMPLES

- Numerous products are designed to be disassembled, from armchairs to dental floss containers. The object must disassemble into components that are in themselves easily recyclable in the case of malfunctioning, or reassembled into new products in cases where they are still functional.

01. Renewable resources

DESIGN PRINCIPLE

Design the product in such a way as to re-inject regenerated material into the system initially used to extract it.
Design the product in such a way that energy extracted from the system can then be regenerated by it.
The energy extracted through the life cycle can be regenerated by the system and in a time less than the life span of the product.

ADVANTAGES

The advantage is that the matter on which the process is based does not run the risk of running out, as long as it does not spoil the ability of the system to regenerate the material. Rational management will limit the taking of matter to a level below which the system regenerates itself.

At a time when conventional fossil fuels are becoming forever more scarce, and when climatic changes are making it perilous to add more carbon dioxide to the atmosphere, a recourse to renewable energy will permit long term supplies while limiting the risks of spoiling the balance of the bio-geophysical cycles, the very basis of our survival.

SAMPLE QUESTIONS

- What are the non renewable materials used in my product?
- What are the properties expected from this material for the operation of the product?
- Can we find a renewable substitute for this material?
- If not, can we rethink the product in order to eliminate the need for this material?
- What sources of non renewable energy are supplying my product?
- Can I find renewable sources that can be used by my product?
- If not, can I rethink my product so as to use a renewable source of energy of a different type?

BIOLOGICAL EXAMPLES

- The majority of living systems call upon renewable materials for their growth. Trees produce carbon based macromolecules and as well as oxygen using carbon dioxide, the latter is produced by breathing organisms, ourselves being one of them. Herbivores consume vegetation (carbon based macromolecules), which then regrows after their passage.
- As with materials, living systems preferentially employ renewable energy sources. Thus photosynthesising plants capture the sunlight, that each day again bathes the planet. Heterotrophs, herbivores like carnivores, capture the energy necessary for their survival by seizing the materials that they need. This energy, like the materials in question, is most of the time renewable. In fact, heterotrophs (as herbivores) nourish themselves with autotrophs, such as photosynthesising plants that for the most part rely on sunlight, or feed on other heterotrophs (as carnivores).

TECHNICAL EXAMPLES

- Renewable materials such as wood, straw, cotton, or microscopic algae biomass, have long been present in the technical world.
- Renewable energy forms part of the energy sources used by industry: solar, hydraulic, wind, biomass...

02. Recyclable and recycled material

DESIGN PRINCIPLE

Design the product so as to use both recyclable materials.
AND
Design the product so as to use recycled materials.
AND
These recycling channels for the materials in the product are designed in parallel to my product, or are already operational.
AND
This recycling channels are designed to limit energy consumption, loss of material and the downgrading of its properties.
AND
The recycling of materials from a component is only carried out if the latter is no longer functional.
AND
Open and closed loops : Recycled materials issuing from my products at their end of life can be reintegrated into new examples of my product as well as into other types of products.

ADVANTAGES

Recycling permits circulation of materials that otherwise would simply accumulate unused. Such stocks, at best, would be inert, but more probably would be a source of toxicity for the environment around the place of storage. Moreover, for some materials, such as aluminium, there are real advantages in terms of material and energy when recycled: the environmental and social cost of extraction of the material being much greater than the cost of its recycling.

The use of recyclable materials is interesting, since these materials, at the end of their life, can potentially be re-used by other actors after recycling. Using recycled materials is logical: rather than depleting stocks of as yet unexploited materials, the product employs material already having been through one cycle in the technosphere. The energy costs of recycling are generally less than extraction for a certain number of materials, so there is thus a potential energy benefit.

However recyclable materials, if they never end up in the recycling channel, or worse if the channel does not exist, are pointless. Integrating both material and energy efficiency of the recycling channel into the choice of materials allows savings to be made which may prove substantial.

Moreover, the entire disassembly of a functional component right down to its basic materials, and then reassembling it from that material into an identical component is simply inefficient. It makes more sense to put in place an infrastructure that salvages functional components which are then reintegrated in their state into the production process.

BIOLOGICAL EXAMPLES

- Living systems function for the length of the life cycles of materials organised in hierarchies. The autotroph (self-feeding) organisms use simple nutriments and solar energy to produce complex carbon based chains. Heterotrophs feed on the complex carbon based chains produced by the autotrophs. They degrade these carbon based chains, partially through the activity of symbiotic micro-organisms, breaking the chains into less complex nutriments. It is not unusual for heterotrophs to integrate quite complex components, such as small protein fragments, providing these are reusable in that state by their metabolism. Living systems recycle, within the framework of their normal metabolism, only degrading materials to a level judged pertinent.

- We humans are made up 100% from recycled materials. We eat only living organisms that are at the end of their life span, and then use their materials to construct ourselves.

- The stomach, during digestion, captures fragments of proteins known as peptides without breaking them down into amino acids. These peptides are then directly used as fragments from which to construct new proteins.

- Humus can be defined as a heterogeneous mixture of recycled materials and during its recycling it serves as a source of material for numerous species. Thus, a lime tree that rots on the floor of the forest can liberate organic material that will benefit other lime trees, but may also benefit mushroom species.

SAMPLE QUESTIONS

- What non recycled materials are present in my product?
- What are the properties expected from these materials for the operation of the product?
- Can we find recycled substitutes for these materials?
- If not, can we rethink the product in order to eliminate the need for these non recycled materials?
- How to organise the collection of the material to be recycled at the end of the life cycle of my product?
- Are the selected materials those which can be recycled most efficiently (in terms of energy, materials, downgrading)?
- Which components are recycled while their components are still functional?
- What are the non recyclable materials present in my product?
- What are the properties expected from these materials for functioning of the product?
- Can we find recyclable substitutes for these materials?
- If not, can we rethink the product so as to eliminate the need for these non recyclable materials?
- Why? Is it a fault in the disassembly process?
- **Is it possible to rethink the product, its assembly and disassembly, in order to only recycle materials from dysfunctional components?**

TECHNICAL EXAMPLES

- Numerous materials in our industrial metabolism are recyclable: glass, aluminium, some plastics. The majority of these recycling processes require large quantities of energy, may lead to spillages, and may result in the case of some materials in a considerable loss in quality through attrition.
- Fungea, a Canadian start-up based in Toronto, produces kits for mushroom production based 100% on recycled materials: the substrate of the product is produced from organic waste, and the packaging from recycled paper and recycled bio-degradable bio-plastics.
- Aluminium is a typical example of a material that can operate in both open and closed loops. From Apple computers to Budweiser beer cans, including some door handles and saucepans, all are made of aluminium. This material is recycled at low energy cost and without degrading its quality, and is thus widely diffused in the technosphere between the life cycle of two objects.
- The waste sorting corporate Juratri, located in the French Jura, has begun a partnership with Envie, a salvage company for the repair and resale of household equipment. Juratri is in charge of the collection and recycling of electrical and electronic wastes that they salvage from the machines that they collect. The still functional products and components are then re-used by Envie, either by the direct sale of spare parts, or by repairing defective models that are then put back on the market.

03. Locally available resources

DESIGN PRINCIPLE

Design the product so that the materials used can be locally sourced.
Design the product so as to capture, transform and/or consume the nearest local energy available.
In the case of a mobile product, the entire life cycle, apart from its use phase, takes place on the same site.
In the case of a fixed product, the entire life cycle takes place on the same site.

ADVANTAGES

Energy and material costs of transport, as well as CO2 emissions are much reduced in case of locally available resources.

SAMPLE QUESTIONS

- What are the most distant sources of materials and energy that supply my product?
- Can I find local usable sources for the product?
- If not, can I rethink my product in order to use a local primary energy source of another type?
- What are the properties expected from the material used in the functioning of the product, and can I find local substitutes for these materials ? If not, can I rethink the product so as to eliminate the need of these non local materials?

BIOLOGICAL EXAMPLES

> A local flow of matter is a tendency among living organisms, which both feed on and eject a flow of matter in a restricted space around their position, whether they are fixed or mobile. Even migrating animals feed directly according to their position and emit their waste locally.

> Function wise, living systems frequently rely on local sources of materials as far as possible. Trees capture CO2 present in the immediate atmosphere and the minerals in the soil in contact with their roots. Even animals with a means of locomotion largely limit themselves to those materials present in their immediate environment. Herbivores consume the vegetation in close proximity, carnivores hunt within their territory and are only displaced by pressure from tenacious competitors.

> As with the materials used, the sources of energy captured by living organisms are often in immediate proximity to their perimeter of action. Photosynthesising vegetation captures the sunlight touching its leaves. The heterotroph, whether herbivorous or carnivorous, captures the energy needed for its functioning at the same time that it captures the material that allows its regeneration.

TECHNICAL EXAMPLES

> There's a trend in the construction industry to preferably use local materials, as is the case in eco construction where compressed earth or straw is employed.

> Locality is not a main characteristic of industrial metabolism. However, some exceptions do exist. Construction projects based on materials extracted on-site (particularly compressed minerals) are multiplying. A Paris region enterprise, Ennesys, offers a local energy production system based on microscopic algae, wastewater and carbon dioxide collected building wide.

> Local energy capture is amply demonstrated in technical systems such as domestic wind generators and solar panels.

04. Non-fossil sourcing

DESIGN PRINCIPLE

The product life cycle relies on (i) solar radiation in the form of sunlight or heat, and/or (ii) thermal or mechanical energy made available by sunlight, and/or (iii) energy arising from the breaking down of the surrounding biomass while salvaging the thus degraded materials for functional purposes.
The materials employed issue from non-fossil carbon.

ADVANTAGES

Moving away from fossil fuel resources, which costs inevitably raise, can offer economic advantages over the long term as well as providing a strong positive ecological impact.

Sunlight illuminates the entire planet; its direct and indirect energy (transformed or stored by other organisms) is thus an energy source that is easy to access. Biomass is simply solar energy transformed and stored in a chemical form.

This reasoning can similarly be used for oil, which is in fact merely fossilized biomass.

Less than 1% of the dying biomass sediment, which means that over 99% of the living matter is entirely recycled as fuel and matter.

Thus, fossil fuels are inevitably more costly to extract and store than biomass. They are also less well distributed over the planet. Moreover, not having been used for millions of years, this gigantic stock of carbon being suddenly liberated is disturbing the bio-geophysical cycle.
We therefore choose to concentrate on the energy and material flows used by living species.

SAMPLE QUESTIONS

- To what extent do I rely on fossil fuels to design and sell my product?
- Can I substitute fossil fuels by either solar or biosourced ones?
- If not, can I rethink my product in order to be able to substitute fossil fuels?

BIOLOGICAL EXAMPLES

Sources of matter and energy in living systems are:

- Solar radiation (sunlight): photosynthesising plants and organisms use sunlight to assemble atmospheric CO2 into carbon based macro-chains.
- Solar radiation (heat): poïkilotherm species (animals regulating their internal temperature via external means) such as reptiles, use heat from the sun to power chemical processes in their organism.
- Indirect solar energy (thermal or mechanical): poïkilotherm species also heat themselves on rocks heated by the sun. Birds and fish use atmospheric and marine thermal and mechanical currents to move around thus spending less energy.
- Biomass: all heterotroph (humans along with other mammals, birds, fungi, reptiles, etc.) use mostly biomass as a source of both matter and energy.

TECHNICAL EXAMPLES

- Agro-resource enhanced value: wood industry, plastics based on vegetal matter, EcoCradle, packaging based upon the Mycelium mushroom species.
- Products using each type of energy (but whose principal function is not to produce energy):

  - Solar radiation (sunlight): solar panel powered lamps
  - Solar radiation (heat): passive heating of houses
  - Indirect solar energy: gliders, aircraft operating without engines and using solely atmospheric mechanical or thermal currents
  - Fermentation, Biogas

05. Mutualized sourcing

DESIGN PRINCIPLE

Material and energy procurement, extraction, transformation and recycling share common channels.

ADVANTAGES

Savings in material and financial resources.

SAMPLE QUESTIONS

- Which resources linked to my product could be mutualized?
- Are these resources already used in other processes of my own, or of my potential partners?

BIOLOGICAL EXAMPLES

- Mutualistic interactions are vital for terrestrial ecosystem function as more than 48% of land plants rely on mycorrhizal relationships with fungi to provide them with inorganic compounds and trace elements.
- The ungulates benefit from the cellulase produced by the bacteria in their intestine, which facilitates digestion; the bacteria benefit from having a stable supply of nutrients in the host environment. Humans also engage in mutualisms with other species, including their gut flora without which they would not be able to digest food efficiently.

TECHNICAL EXAMPLES

- The industrial symbiosis of Kalundborg in Denmark:
  Six different organisations grouped together since the 1970s:
  1. Town Hall
  2. Asnaes, power station
  3. Gyproc, plaster manufacturer
  4. Novo, pharmaceutical company
  5. Bioteknisk Jordrens, contaminated soil remediation company
  6. Statoil, petroleum refinery

  A dense network of exchanges is developed on this site via the by-products issuing from diverse industrial and human activities: steam, water, refinery gases, synthetic gypsum, biomass, liquid fertilizer, fly ash from the coal burning power station, muds from the water treatment plant, etc.
- Dalkia is about to construct a new energy recovery network based on the data centre of a banking establishment. It will recover the large volumes of warm air generated by the refrigeration units and enhance their value via the production of hot water and central heating for neighbouring offices.
  Dalkia intends to put in place several heat exchangers having a total power of 7.8 MWt. In the long term, this network will supply 26,000 MWh per year and heat almost 600,000 m2 of buildings, thus reducing the carbon footprint by 5,400 tons of CO_2 each year.

06. Local export

DESIGN PRINCIPLE

Design the product so that the materials produced can be exported locally.
If the product is energy positive, it is designed and integrates its environment so that the energy it captures and/or transforms is used as locally as possible.
The energy produced during the life cycle of the product serves primarily to satisfy energy needs linked to the life cycle of my product.

ADVANTAGES

If a material finds a local outlet in the region where it is produced, material and energy costs of transport are reduced by this local export.

Transporting energy can have high material and energy costs. Since energy needs are virtually universal, exporting as locally as possible is therefore a simple means of generating potentially considerable savings in materials and energy.

SAMPLE QUESTIONS

- If my product produces material or energy, is it exported locally? If not, why?
- What could be the direct use of such material or energy by my product?
- Can I invent a new function for my product so that it will employ this material or energy?
- Can this material or energy be used by another in proximity to my product?
- What types of processes is this material or energy involved in?
- What sort of economic or industrial actors could be interested by the proximity of this material or energy resource?
- How can I better use information sharing to increase the potential of my product to be locally used?

BIOLOGICAL EXAMPLES

- When living organisms reach the end of their life cycle, they are generally decomposed locally by various composting organisms; these in turn make organic material available to other living organisms. Such is the case, for example, of trees that fall to the forest floor.
- Trees, which capture the sun’s energy for growth and to power their metabolism, use it first and foremost to survive, then store a part in the form of carbon based macromolecules and exchange a fraction with other organisms via their root system and organisms in the soil.

TECHNICAL EXAMPLES

- The Fungea start-up exports its mushroom production kits (made from locally recycled materials) only within a 100 kilometre radius. Any further afield, it sells licences to local entrepreneurs who then handle the kits’ production.
- The Biolite wood fired cooking stove is quite unusual. To optimise combustion, air is blown through the fire by a fan bringing in extra oxygen. This fan is powered by a battery which itself is recharged by a thermo electric generator using the Seebeck effect, i.e., the heat of the flames generating the power. The more air that is blown through the flames the stronger the combustion, the greater the heat generated and thus the greater the power generated. The excess power can be accessed via a USB port on the stove and can be used to recharge small electronic devices (useful when hiking). In this instance, the energy is primarily used by the product itself (charging the fan battery, essential to the efficiency of the combustion) and then the excess is secondarily exported for other purposes.

07. Materials compatible with the living

DESIGN PRINCIPLE

Designed the product so as to use bio-compatible materials.

ADVANTAGES

Bio-compatible compounds are, by definition, non toxic on the long term for our own and other organisms in the biosphere, this provides considerable benefits in terms of health.

SAMPLE QUESTIONS

- Which materials linked to the product are clearly not bio-compatible?
- What are the properties expected of these materials in the operation of the product?
- Can we find bio-compatible substitutes for these materials?
- If not, can we rethink the product so as to eliminate the need for these non bio-compatible materials?
- If the materials are bio-compatible, am I sure that their level of release in the environment are not causing known environmental problems?

BIOLOGICAL EXAMPLES

> The great majority of materials of biological origin are bio-compatible.

TECHNICAL EXAMPLES

> Biomaterials used in the medical field must be compatible with the body, and there are often issues of biocompatibility which must be resolved before a product can be placed on the market and used in a clinical setting. For example, biomaterials are used in: joint replacements, bone plates and cement, artificial ligaments and tendons, dental implants for tooth fixation, blood vessel prostheses, heart valves, skin repair devices (artificial tissue), cochlear replacements, contact lenses, breast implants, drug delivery mechanisms, sustainable materials, vascular grafts, stents, nerve conduits…

08. Green Chemistry

DESIGN PRINCIPLE

"Green Chemistry" promotes innovative chemical technologies that reduce or eliminate the use or generation of hazardous substances in the design, manufacture and use of chemical products. Its main focus areas are: (1) the use of alternative synthetic pathways, (2) the use of alternative reaction conditions and (3) the design of safer chemicals that are less toxic than current alternatives or inherently safer with regards to accident potential. In 1998, Paul Anastas and J.C.Warner announced a set of 12 principles as a useful guide to design environmentally benign products and processes and to evaluate the already existing processes. It is of high interest to notice the resemblance of those principles to the chemistry of the living that has been described for decades.

08/1. Operation under mild conditions

DESIGN PRINCIPLE

Processes related to my product take place at ambient temperature and pressure.

ADVANTAGES

Processes taking place at ambient temperature and pressure have the advantage of limiting the amounts of external energy needed (to increase/decrease the pressure/temperature). Such processes also offer the added advantage of reducing entropy during the reaction.

SAMPLE QUESTIONS

- Which processes linked to my product do not take place at ambient pressure and temperature?
- Can I substitute these processes for ones taking place at ambient pressure and temperature?
- If not, can I rethink my product in order to eliminate the need to resort to this process?

BIOLOGICAL EXAMPLES

- While technology often employs extremely high or low temperatures and pressures, all living systems assemble teeth, bones and shells at ambient temperature and pressure. Moreover, the properties of certain of these ceramics, in terms of being fracture resistant, are considerably more efficient than artificial ceramics. This is the case with abalone, a crustacean found in the ocean.

TECHNICAL EXAMPLES

- Many examples of bio-inspired chemistry are described in the literature, most of which rely on cellular metabolism mimicking (enzymes, catalysts) especially in the white biotechnologies field. They have permitted the development of numerous synthetic chemical processes that take place at ambient temperature and pressure.

08/2. Water as solvent

DESIGN PRINCIPLE

The processes relating to my product is designed in such a way as to employ water as the solvent.

ADVANTAGES

Water is omnipresent on the surface of the planet, since life began and has evolved in an aqueous medium. It is thus the most universal and least toxic solvent.

SAMPLE QUESTIONS

- Which processes linked to my product do not use water as the solvent?
- Can I substitute these processes by others using aqueous solvents?

BIOLOGICAL EXAMPLES

- Most living cells are composed 70% of water. Most of the essential molecules of life dissolve and transport easily in water. Water participates in all kinds of biochemical reactions. Bounded by water insoluble membranes, cells owe their shape and rigidity to water. Water also provides the supply of hydrogen ions needed for converting the sun's energy into chemical energy.

TECHNICAL EXAMPLES

- According to Biomimicry 3.8, Bayer has succeeded in developing a polyurethane coating that uses from 50% - 90% water as its solvent.

08/3. Abundant atomic elements

DESIGN PRINCIPLE

The products are made from abundant atomic elements.

ADVANTAGES

The use of locally abundant elements facilitates extraction, supply, recycling and/or assimilation by living organisms of the materials thus produced.

The use of compounds with a biological origin, bio-compatible and biodegradable, provide other advantages when using materials already tested and selected by living systems in order to be compatible with the majority of them. This avoids the development of more dangerous compounds (even if organic) whose unfortunate consequences can leave long term effects, as well as also becoming lost in the astonishing complexity of cause and effect that weaves throughout processes in the biosphere.

SAMPLE QUESTIONS

- Which processes linked to my product do not use abundant substance?
- Can I substitute this substance by another one?

BIOLOGICAL EXAMPLES

- Living species are more than 95% organic matter (oxygen, hydrogen and nitrogen), and only marginally resort to metals and other rarer atoms. Even mineral processes such as those of ceramic shell formation, are controlled and structured by organic matrices that confer exceptional properties on them. We see the omnipresence of certain materials in the biosphere: nucleic acids, their sugars and nitrogen compounds; proteins and their amino acids; inorganic phosphates and their derivatives that play a fundamental role in energy metabolism; phospholipids making up plasmic membranes, and so on. This large base of shared material leads to high degrees of compatibility between living organisms, and thus permits the exchange of nutriments, as is the case, for example, between trees and fungi, as well as numerous other symbiotic exchanges.

TECHNICAL EXAMPLES

- As a material, carbon fiber has fundamentally changed many of the products we use every day, making them lighter and stronger. But the manufacturing process is generating a great ecological impact. However, this shows that it is possible to re-design manufacturing processes using and not emitting carbon, like the rest of the biosphere.

- CO2solstock is an FP7 EU- financed funded R&D project launched in response to the common concern of Climate change. The scientific teams involved in this project investigate on sustainable bio-inspired solutions for carbon sequestration. They especially focused on biomineralization of carbon by microorganisms, in particular the natural properties of some bacteria to combine calcium and CO2 to produce calcareous rocks. Moreover, the project includes the aspects of valorization of the produced calcium carbonate, for example for real estate and building construction.

08/4. Enzyme catalysis

DESIGN PRINCIPLE

The production of chemical compounds is based on enzymatic catalysis.

ADVANTAGES

The use of enzymatic catalysis allows operation at moderate temperatures and pressures, with aqueous solvents, accelerates chemical reactions, and reduces the number of reaction stages needed, as well as ensuring selectivity in the reaction.

SAMPLE QUESTIONS

- Can I substitute or skip synthesis phases using enzyme catalysis?

BIOLOGICAL EXAMPLES

- An enzyme is a protein that plays the role of a biological catalyst, i.e., a compound facilitating a biochemical reaction without modifying the products. It is capable of lowering the energy activation threshold of a reaction and thus accelerating chemical reactions of the metabolism millions of times, without modifying the balance formed. Enzymes operate at low concentrations and remain intact at the end of the reaction. They ensure a total selectivity in the reaction even within complex mixtures such as intracellular milieu. These cascading enzymatic reactions permit a cell to respond in an adequate manner to a given stimulus and within a very short lapse of time.

TECHNICAL EXAMPLES

- The so-called white biotechnologies, use enzymes as industrial catalysts to either produce valuable chemicals or destroy hazardous/polluting chemicals. White biotechnology tends to consume less in resources than traditional processes used to produce industrial goods.

09. Additive manufacturing

DESIGN PRINCIPLE

Additive Manufacturing refers to a process by which a product is made layer by layer by depositing material. 3D printing is an example of additive manufacturing.

ADVANTAGES

During production of a given object, additive manufacturing reduces wastage of material to the maximum.

SAMPLE QUESTIONS

- Which manufacturing processes linked to my product do not operate through material addition, i.e., additive manufacturing?
- Can I substitute them for processes using additive manufacturing?
- If not, can I rethink my product in such a way that its manufacturing process operates via the addition of material?
- If yes, can I use renewable and environmentally friendly, or at least recycled raw materials?

BIOLOGICAL EXAMPLES

- The bones of the cuttlefish self-assemble through the progressive crystallisation of ions dissolved in sea water.

TECHNICAL EXAMPLES

- 3D printers operate by employing additive manufacturing. Instead of carving an object from a solid block, it is printed in consecutive layers. A range of different materials may be used and the technology presents a cost-saving potential and the ability to meet sustainability goals if the materials are carefully selected.

10. Biodegradable materials

DESIGN PRINCIPLE

The product uses biodegradable materials.
AND
The composting channels that accept the biodegradable materials from my product at the end of its life cycle are either designed in parallel to the product, or are already operational.

ADVANTAGES

Living organisms can breakdown biodegradable material at the end of its life cycle. The products of such bio-degrading can be assimilated by other living organisms, this permits a linking of the technological matter loop to the flow of biological matter. The advantage of this is that it does not definitively remove any matter from circulation within the biosphere. Synergy between the biosphere and the technosphere is thus easier.

The ease of assimilation, or its metabolizable attributes, already implies a form of edibility by definition, which implies the non-toxicity of the materials and their breakdown products.

However, any interest in using biodegradable materials is limited if they do not link up with a composting channel.

SAMPLE QUESTIONS

- Which materials linked to the product are not biodegradable?
- What are the properties expected of these materials as regards operation of the product?
- Can we find biodegradable substitutes for these materials?
- If not, can we rethink the product in order to eliminate the need for these non biodegradable materials?
- How to organise the composting of biodegradable materials contained in my product?

BIOLOGICAL EXAMPLES

- An immense proportion of materials produced and consumed by living organisms are biodegradable: wood, skin, leaves, hair, etc. Only mineral materials such as teeth, bones or shells have a longer persistence in the environment, and are for the most part inert and non-toxic to neighbouring living organisms.

TECHNICAL EXAMPLES

- Wood and paper are biodegradable (and bio-sourced). Certain bio-plastics claim to be biodegradable, particularly maize or potato starch based products, such as Ecoflex plastic.
  However, biodegradability is still a poorly defined concept, and some materials are broken down into microscopic fragments that cannot then be metabolised by living organisms and whose toxicity still is uncertain. It is therefore necessary to handle the concept with precaution when advanced in the technosphere.

11. Energy provider

DESIGN PRINCIPLE

The product is capable of capturing or producing energy.

ADVANTAGES

Making each product an energy producer, even if the power produced is only a fraction of what it consumes, contributes to the overall resilience of the energy system, by distributing, diversifying (depending on the nature of the product) and by increasing the redundancy of energy producing units.

This allows a reduction in dependency on major centralised power production, often based on fissile or fossil fuels.

SAMPLE QUESTIONS

- What are the energy sources available in the immediate environment of my product?
- Could certain co-products of the process used by my product become a source of energy?
- Which processes allow the transformation of available energy into useful energy for my product?
- Are synergies possible between these processes and those used by my product?
- Can I rethink my product by integrating an energy production system?

BIOLOGICAL EXAMPLES

> The majority of living organisms are capable of capturing, producing or transforming energy. Our organism recovers energy from the breaking down of the macromolecules that we assimilate during meals. We store excess energy as glycogen in the liver, and in the form of fat. Photosynthetic vegetation captures sunlight and stores the surplus in the form of carbon based macromolecules. No organism alive has only the function of energy production, but the majority of organisms handle at least a part of their energy supplies.

TECHNICAL EXAMPLES

> Numerous products on the market are capable of capturing, storing and producing energy: lamps with their own solar panels, energy positive buildings, a wood stove using a thermoelectric effect to recharge small electronic devices via USB...

12. Diversity of storage and distribution strategies

DESIGN PRINCIPLE

The product functions are ensured using both diversity of resource storage (in particular energy) and diversified distribution strategies.
This involves an efficient coordination of both stores and distribution channels.

ADVANTAGES

Relying on several storage and distribution strategies allows being both more adaptable and efficient depending on usage, and more resilient in case one channel is dysfunctional.

SAMPLE QUESTIONS

- Does my system rely on diversified and decentralized resources?
- Is my system able to sense changes which would require adaptation?
- If yes, is it able to efficiently process the information in order to respond properly?

BIOLOGICAL EXAMPLES

- **Energy :**
  Locally, there are obviously big fluctuations in direct solar energy between night and day, seasonal variations, availability of food. Consequently living organisms all store energy mainly through conversion to fat and carbohydrates and manages fluctuations in energy supply by metabolizing and growing only when energy is available, and in an individualized scheme.

- **Information chains :**
  Life relies on two kind of information chemical chains which work in a loop : information chains, DNA, which provide genetic description, and their translation into working chains, the proteins.
  Living organisms need to maintain constant temperature, to replace parts, to defend against aggression, to get energy, to move, … DNA and genes contain no information on these, but contain the information on how and when to make the proteins. The rest is up to proteins. Depending on the DNA sequence, different proteins are produced : enzymes- catalysts, transporters, movers, supporters, regulators, defenders, communicators
  Life runs on multi-layered loops of control : Every biological circuit, whether a sequence of proteins, or a complex ecosystem exhibits self correcting tendencies. Information flows around the circuit and feeds back the starting point, making necessary adjustments.
  In living systems, information circulation can rely on electric, visual, acoustic signaling, all resulting in intra (enzymatic cascade) or inter cellular (hormones, neurotransmitters…) chemical processing.

TECHNICAL EXAMPLES

- Human systems start using smart control systems like the currently developing smart grids, and multiplying small and local powering systems (wind power, solar panels, methanation…), instead of classical centralized power plants.
- Renault Automotive recently initiated collaboration with a physiology lab, in order to mimic the way that human body mobilises its energy stocks depending on requested efforts, and imagine a new generation of hybrid engine.
- In human technologies, several signalling pathways are used, but mostly physical: electric, electromagnetic, accoustic…

Solving a specific technical challenge

Having read previous chapters, the reader should have:

- A list of criteria to work on
- Paths for potential innovation projects to improve its products

Or the reader may have already defined a specific technical challenge he/she would like to solve looking at living systems.

In spite of an increasing number of researchers and users in the field of bio-inspiration, the transfer of knowledge from the field of biology to technology is still a complex process. It starts by linking a biological model to a specific technical question and the successful application of bio-inspiration follows several systematic steps:

1 CLEARLY DEFINE THE CHALLENGE FROM A FUNCTIONAL POINT OF VIEW

2 IDENTIFY THE BEST BIOLOGICAL MODEL(S)

3 ABSTRACT AND EMULATE INTO HUMAN TECHNOLOGIES OR SYSTEMS

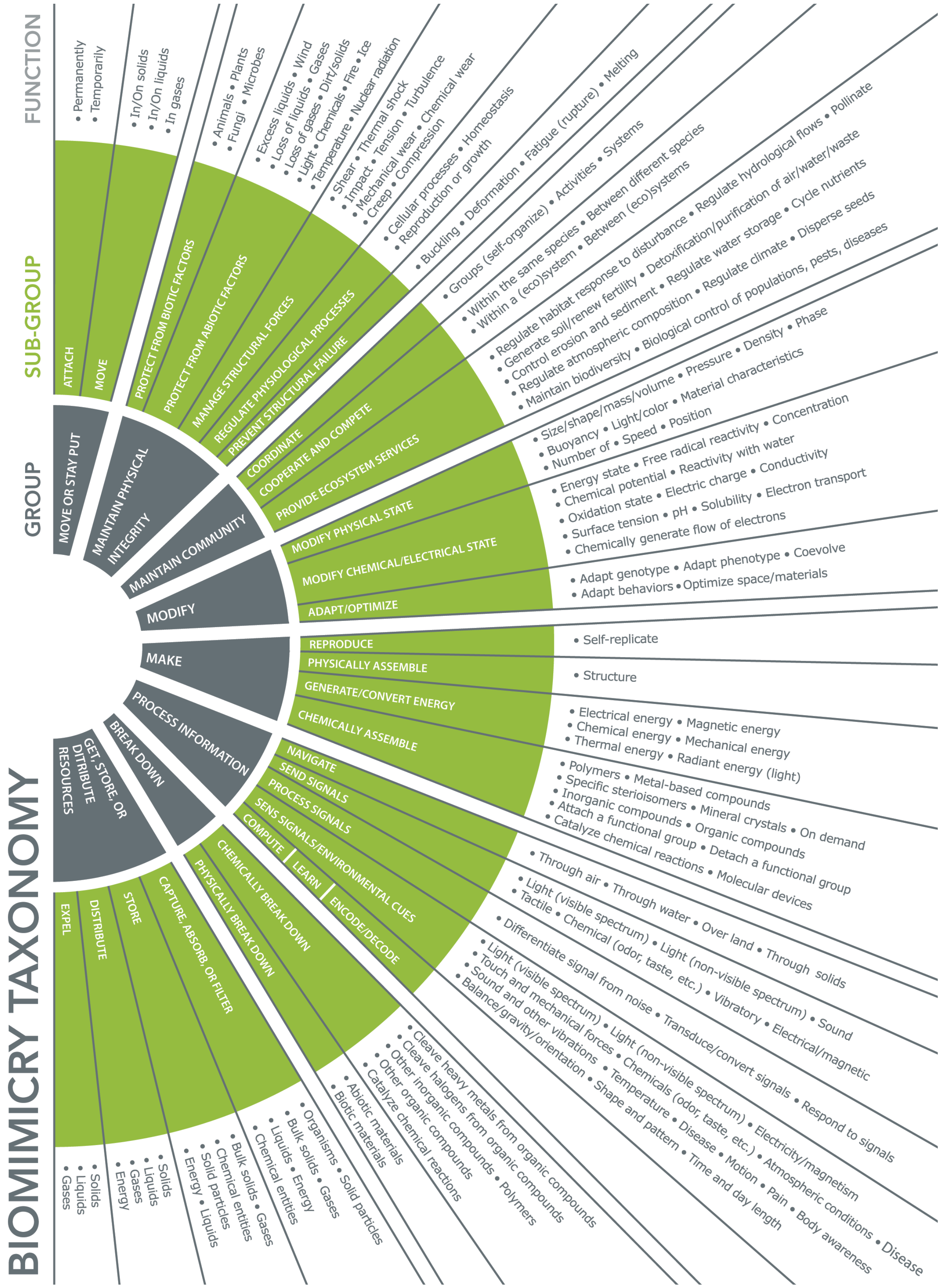
4 CHECK FOR SUSTAINABILITY

The field of biomimetics is highly interdisciplinary, which is indicated by the high level of required cooperation between experts from different fields of research: biologists, chemists, physicists, and engineers. **Bio-inspiration cannot be effective without involving biologists during the innovation process.**

Biomimicry offers ideas and not finished solutions. Nowadays the formalization of Biomimicry, whether considered as a concept or a science, follows a path of hybridization with design theories. Three of them have already been tested and described in the literature: CK theory, TRIZ theory and semantic approach. In the context of that manual, these tools will not be presented. Please refer to “bibliography and resources” section for more details.

STEP 1: FUNCTIONAL DEFINITION OF THE CHALLENGE

The first key stage in any bio-inspired innovation process is to identify exactly which function you wish to “biomimetize”. The Classification of Biological Functions provided below may help you. It is a list of functions that are found in the living given in a hierarchical order.



STEP 2: FIND BIOLOGICAL SOLUTIONS TO THAT FUNCTIONAL CHALLENGE

Once you have identified the function of a system, you must identify the biological organisms that model this function in biological systems and this is the tricky part.
Powerful database tools are under development, but in the meantime, here are several ways to get your investigation started:

- **Consult existing databases as AskNature, organized by biological function; it is not exhaustive but it is one of the few free resources enabling such systematic search.**
- **Invite biologists to your working groups.**
- **Search through biology scientific articles and manuals. However, they still require to be commented by biologists and are rarely structured as functional or systemic.**
- **Invite specialists of the bio-inspiration field in your working groups, especially those working on competence networks and dedicated problem solving tools. Please see the "bibliography and resource" section.**

STEP 3: ABSTRACT AND EMULATE INTO HUMAN TECHNOLOGIES OR SYSTEMS

Brainstorm and try to find the repeating successful biological patterns and processes and develop ideas and solutions based on that natural models.

STEP 4: DOES MY BIO-INSPIRED SOLUTION FULFIL AS MUCH PREVIOUSLY LISTED CRITERIA AS POSSIBLE ?

Because sustainability character of bio-inspired solutions need to be checked, the emerging solution needs to fulfil previously listed criteria.

BIOMIMICRY GLOSSARY

- **Adaptation**
  the ability of a system to adjust its state or behaviour according to environmental conditions.

- **Self-assembly**
  the absence of human intervention or automated equipment to assemble product's various components.

- **Autotroph**
  an organism harnessing the sun's energy to synthesize its own food from carbon dioxide into organic compounds.

- **Bio-assistance**
  exploiting services from a living system or organism.

- **Bio-inspiration**
  any form of process taking inspiration from the living world.

- **Biomaterials**
  Biomaterials (not to be confused with eco materials) are either materials produced by bio-technologies or materials that are bio-compatible or capable of coexisting with man or animals.

- **Bio-sourced (of a material)**
  material from biomass of vegetable or animal origin.

- **Bio-utilization**
  exploiting materials produced by a natural system or living organism.

- **Bionic***
  functional inspiration taken from one or more living systems with technical performance as its objective.

- **Biomimicry***
  functional inspiration taken from one or more living systems with sustainability as its objective.

- **Biomorphism**
  process seeking inspiration from natural shapes with an aesthetic intention.

- **Biodegradable**
  can be completely broken down by living organisms into nutriments that can be absorbed naturally.

- **Harness (energy)**
  to extract (energy) from raw material or from a primary energy source (e.g. uranium or sun's rays).

- **Concept (design)**
  product in its simple, theoretical or even partial form. Sketch of a potential technical solution still to be implemented.

- **Critical (of component)**
  component whose end of life pushes the whole product to its end of life.

- **Ecofriendly material**
  product whose production process, transportation, implementation, use and end of life offers an overall superior environmentally friendly performance against that of standard materials.

*these definitions are still discussed in the context of the ISO TC 266 biomimetics.

- **Scalability**
  the ability of a system to modify its nature or structure.

- **Function**
  service provided by a system. For example, a washing machine has washing laundry as its function. A washing machine provides a service in washing laundry for us.

- **Heterotroph**
  organism that breaks down complex organic material from autotrophs into compounds to create its own food.

- **Resilience**
  capacity of a system to maintain and regenerate its functions after a potentially destructive event. Maintaining and regenerating functions may occur as an evolution of the nature and structure of the system.

- **Robustness**
  capacity of a system to maintain its functions in a changing environment without any radical evolution in its nature and structure.

- **System**
  combination of interacting components.

- **Living system**
  Biosphere subsystem.

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This manual contents have been adapted from four major sources:

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List of European networks of competences and resources

International networks and centers

BIOKON INTERNATIONAL
A German non-profit organization hosting over 100 major players in the field of bionics and biomimetics in Germany and highlighting international initiatives and measures to build an integrative network of leading experts in the field of biomimetics.
www.biokon-international.com

CEEBIOS
The first European Center dedicated to promote nature inspired solutions to address societal challenges.
Launched in September 2012, the CEEBIOS (Centre Européen d'Excellence en Biomimétisme de Senlis) aims at being a real campus, offering shared spaces for training, research, Start-ups, SMEs and bigger companies.
www.ceebios.com

EUROPEAN BIOMIMICRY ALLIANCE
A trans-national network of European experts in the field of innovation driven by biomimetic approaches.
www.biomimicryalliance.eu

Austria

BIONIK
www.bionikum.at

Belgium

GREENLOOP
The first European consultancy firm dedicated to Biomimicry
www.greenloop.eu

France

In France, about 80 public research departments, many of which are internationally renowned, are working in the bio-inspiration field. In particular, in the Paris Region Area, about 40 laboratories have been identified. There are several pioneer projects or initiatives within corporations or SMEs on the French territory and, within the Paris region area, more than 40 SMEs implementing biomimicry have been today identified.
The Sustainable-development division of the French Ecology Ministry (Commissariat Général du Développement Durable, CGDD) has included biomimicry as a key strategy for environmental transition over 2014-2020.

PARIS REGION ENTREPRISES

The first French public institution to promote Biomimicry as a tool for responsible innovation.
www.paris-region.com

CEEBIOS

Launched in September 2012, the CEEBIOS (Centre Européen d'Excellence en Biomimétisme de Senlis) aims at being a real campus, offering shared spaces for training, research, Start-ups, SMEs and bigger companies.
www.ceebios.com

ACTIVE INNOVATION MANAGEMENT

Creativity tools for bio-inspiration.
www.aim-innovation.com

FRENCH COMMITTEE OF BIOMIMICRY EUROPA, NGO

Non-profit international association established in Brussels in 2006, and then in France, by women and men from a variety of backgrounds and promoting Biomimicry as a tool for environmental and social responsability.
www.biomimicry.eu

INSTITUT INSPIRE, NGO

www.inspire-institut.org

Germany

There are over 100 R&D German public research structures involved in biomimetics activities and two major institutional research networks BIOKON and Kompetenznetz Biomimetik. BIOKON led the central project of the BIONA (Biomimetic Innovations for Sustainable Products and Technologies) funding scheme of the German Ministry of Research and Education, which supports the transfer of innovative biomimetic approaches to sustainable and competitive solutions.

BIOKON and BIOKON INTERNATIONAL

A German non-profit organizations hosting over 100 major players in the field of bionics and biomimetics in Germany and highlighting international initiatives and measures to build an integrative network of leading experts in the field of biomimetics.
www.biokon-international.com

REGIONAL NETWORKS and CENTERS

- Kompetenznetz Biomimetik Baden-Württemberg
- Bayonik Bionik-Netz Bayern
- Bionik-Innovations-Centrum (B-I-C) Bremen
- Bionic Engineering Network (BEN) Saarland
- Bionik-Netzwerk Hessen
- Bionik-Zentrum ‚bionicum' in Nürnberg
- Collaborative Research Center - Transregio 141
- Freiburg Centre for Interactive Materials and Bioinspired Technologies (FIT)

BIOMIMICRY GERMANY

www.biomimicrygermany.de

Italy

> **PLANET**

Nature Inspired Technology
http://planet.wemimic.it

Netherlands

> **BIOMIMICRY NL**

www.biomimicrynl.org

Spain

> **BIOMIMICRY IBERIA**

www.biomimicryiberia.com

United Kingdom

> **BIONIS**

The Biomimetics Network for Industrial Sustainability (BIONIS), gathering over 500 members worldwide, promotes the application of biomimetics in products and services and its use in education and training. The network focuses on several relevant areas regarding environmental transition (energy and resource efficiency, elimination and control of hazardous substances, use of renewable and biodegradable materials, added functionality in materials and structures)

> **BIOTRIZ**

www.biotriz.com

> **BIOMIMICRY UK**

www.biomimicry-uk.org

Useful websites

> **ZYGOTE QUARTERLY**

http://zqjournal.org

> **BIOMIMICRY 3.8**

www.biomimicry.net

> **ASK NATURE DATABASE**

www.asknature.org

> **A reading list of more specialized works on biomimicry, as classified into various disciplines by the BIOMIMICRY INSTITUTE (EN)**

www.biomimicryinstitute.org/downloads

> **ENCYCLOPEDIA OF LIFE**

www.eol.org

> **ISO TC 266 BIOMIMETICS**

First technical committee for international standard on biomimetics
www.iso.org/iso/home/standards_development/list_of_iso_technical_committees/iso_technical_committee.htm?commid=652577

KARIM VIDEOS ON BIOMIMICRY

What is biomimicry ? How is it sustainable ?

www.youtube.com/playlist?list=PLdKr6QgiRl60EctzhfF2PDPYzMMssH5xQ

Biomimicry European Landscape

www.youtube.com/watch?v=xtJGCRAhPxk

CONTACT FOR FURTHER INFORMATION

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ABOUT PARIS REGION ENTREPRISES

Paris Region Entreprises supports the development of businesses delivering the most economic, social and ecological added value. Its missions are:

- To unite players in the Paris Region ecosystem and to coordinate their efforts, so as to optimise prospection work throughout the region and worldwide, as well as the overall growth of businesses within the Paris Region.
- To provide businesses with long-term guidance in their development. Paris Region Entreprises plays a key advisory role for businesses that have specific plans for development.
- To attract foreign companies with growth potential into the Paris Region and assist in their settlement.

Since 2009, Paris Region Innovation Center (merged into Paris Region Entreprises in July 2014) has been supporting the development of Paris Region firms by coaching their projects, which have high economic, social and environmental added value seeing that the projects mature, become structured and get launched.

Paris Region Entreprises has been leading the KARIM Interreg IVB project on Responsible Innovation. Since 2012, Paris Region Entreprises has identified and started to experiment biomimicry as a tool for responsible innovation and a lever for SME competitiveness. Since mid-2012, Paris Region Entreprises has identified, in the Paris region area, over 45 successful SMEs already practicing Biomimicry as a tool for responsible innovation and over 35 academic laboratories running bio-inspired research. Paris Region Entreprises has disseminated the approach over almost 10 talks gathering a total of more than 400 participants.
Paris Region Entreprises has connected with the international European network (universities, competence centers, SMEs…) in the area of bio-inspiration and increased the awareness of the innovation opportunities in the area of novel nature-inspired and environmentally friendly technologies.

INTERREG IV B - 207G - KARIM
KARIM Project is co-financed
by the European Union.