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Thesis Title:

A PROBLEM SOLVING METHODOLOGY FOR THE DEVELOPMENT OF BIO-INSPIRED PRODUCTS

Systematic use of "Natural Design Principles" for designers without Biological Knowledge

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A nonna Maria

Che, senza saper leggere,
Mi ha saputo insegnare
L'ABC della vita

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Abstract

The observation of Nature to learn how to solve technical problems has been something that has characterized all the history of the humankind. In the XIX century, the new possibilities given by the latest technologies i.e. production systems, materials etc. allowed scientists using Nature as a model to realize technical reproductions of Nature's solutions.

Nowadays, the use of Nature as a Source of Inspiration for the development of new solutions cannot be left to the "chance". In the last decades, the Bio-Inspired Design (BID) research has been focused on the development of methods and tools for the systematic use of natural information.

Accepting the hypothesis that Nature's solutions can be a source of innovation in the product development process, the main research question is the following: *How to systematically conceive a new Bio-Inspired Product?*

The scientific community has developed several tools for the BID tasks. Unfortunately, despite that, these are singularly effective and it has not been developed a methodology that groups them and allows a systematic use.

The present research has been aimed at the integration of the most appropriate BID tools into a Problem-Solving Methodology that can be used by designers without Biological knowledge.

The methodology's targets are the SMEs and the young designers that are at their first Design experiences and that do not have any specific expertise in biology. At last, the methodology proposed is suitable for the development of technical products.

The proposed methodology adopts a set of tools i.e. The NIST Functional Basis: a standardized set of function-related terminology, the Biomimicry Taxonomy (BT): the classification system used by the Biomimicry 3.8 Institute to organize the information about the Natural Sources of Inspiration (NSoI) and the NIST-BT Correlation Matrix. Thanks to these tools, it is possible to systematically carrying out a new Bio-Inspired Design that starts from a technical problem in order to develop a Bio-Inspired Conceptual Solution. Among the proposed tools, some of them have been simply selected or improved and others have been specifically developed for the methodology, such as the NIST-BT correlation matrix that allows translating the technical problem in biological terms.

The methodology's validation has been obtained by combining two validation approaches:

A. Ability of the methodology to guide the generation of the Bio-Inspired Conceptual Solution

I. *Usability of the "Nature's Solution(s)" during the Design Phase*
II. *Multiple requirements satisfaction approach*
III. *Effectiveness of the methodology*

B. Fulfilment of the project requirements by the developed Bio-Inspired Conceptual Solution

Three designers from the Institute of Product Development (Lehrstuhl für Produktentwicklung) of the TUM Technische Universität München have individually applied the full methodology on a set of four Test Cases. Furthermore, a tools' use validation has been obtained by a set of experiments carried out by two Control Groups corresponding to the target designers.

As an output of the research, it has been obtained a methodology that collects the most appropriate tools in order to carry out the necessary BID tasks to systematically conceive a new Bio-Inspired Product.

The most relevant aspect of the methodology is that no *Biological Knowledge* is necessary to perform the BID. This result has been obtained by the use of the NIST-BT Correlation Matrix combined with the approach adopted to perform the search in the database of Natural Phenomena. Furthermore, no knowledge about *Biological Keywords* or Natural Phenomena is needed to perform the search. Finally, this tool has been validated showing that the problem reframing in Biological terms is robust in terms of output quality.

In order to improve the capability of the models used for BID tasks, it has been proposed a SAPPhIRE-DANE integrated model. The new model has been used to describe all the 13 NSoI individuated. Thanks to the structured description of the *Natural Information*, the designers have been able to solve singularly each problem and no compromise solutions have been adopted. With the extraction of the natural information represented in the items of the models, it has been possible to individuate a specific solution for each technical problem.

The methodology has been effective both in terms of time and in the number of Bio-Inspired Conceptual Solutions developed i.e. four out of four, which satisfy all the correspondent requirement lists. Moreover, it is suitable for supporting the solution of both ordinary and inventive technical problems. At last, the method can be inserted in the standard Product Development Processes in order to systematically use Nature as a source of inspiration.

The methodology has shown some limitations. For example for the designers: no mental inertia and a basic knowledge on functional modelling are required. Besides, the search can be done into a limited number of natural phenomena i.e. ≈2000.

With the aim of reducing the gap between academic research and industry, stringent constrains have been imposed to the methodology. First, the methodology has to be able to support individuating the correct NSoI also without Biological Knowledge. In fact, the use of the BT-NIST correlation matrix allows the creation of direct link between the design problems expressed in technical terms and the correspondent class of "Nature's Solutions". Second, the methodology can be adoptable by the SMEs that usually have low budgets, that imply no possibility to hire consultants, or biologists specialized in solving technical problems and, have free or low budget tools.

At the moment, the methodology is paper based and the logical future development is the implementation of the methodology in an IT tool.

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AI	**A**rtificial **I**ntelligence
B	**B**ehaviour
BID	**B**io-**I**nspired **D**esign
BIP	**B**io-**I**nspired **P**roduct
BT	**B**iomimicry **T**axonomy
CD	**C**onceptual **D**esign
CPD	**C**ausal **P**rocess **D**escription
CS	**C**ase **S**tudy
DANE	**D**esign by **A**nalogy to **N**ature **E**ngine
F	**F**unction
FB	**F**unctional **B**asis
FBS	**F**unction-**B**ehaviour-**S**tructure
FR	**F**unctional **R**epresentation
NIST	**N**ational **I**nstitute of **S**tandard and **T**echnologies
NIST-FB	**NIST-F**unctional **B**asis
NSoI	**N**atural **S**ource **o**f **I**nspiration
OED	**O**xford **E**nglish **D**ictionary
PB	**P**ro**b**lem
PDD	**P**roduct **D**esign and **D**evelopment
PDP	**P**roduct **D**evelopment **P**rocess
PS	**P**umping **S**ystem
RL	**R**equirements **L**ist
RQ	**R**esearch **Q**uestion
S	**S**tructure
SAPPhIRE	(change of) **S**tate-**A**ction-**P**art-Physical **Ph**enomenon-**I**nput-o**R**gan-Physical **E**ffect
SME	**S**mall-**M**edium **E**nterprise
SoA	**S**tate **o**f the **A**rt
TC	**T**est **C**ase

Introduction

> *[…] The genius of man may make various inventions, encompassing with various instruments one and the same end; but it will never discover a more beautiful, more economical, or a more direct one than nature's, since in her inventions nothing is wanting and nothing is superfluous. […]*

Extracted from The Notebooks of Leonardo (Richter, 1952, p. 103).

There is a general belief that says Nature has already solved all the problems that the humankind has encountered, is having and will face in the future. It is true that in Nature […] *some animals produce structures showing design … but all are results of evolutionary pressure and not of conscious thought* […] (French, 1994). Nevertheless, this does not mean that Nature has problems to solve!

So why develop a PhD thesis on a Problem-Solving methodology in order to systematically conceiving Bio-Inspired Products?

Evolution implies that Nature is the biggest and most fruitful laboratory for the Trial & Error processes. This laboratory, which is working since 3.8 billions of years, has developed solutions for all the evolutionary challenges. These ***Nature's solutions*** have been a constant source of inspiration for the humankind all over its history. Because Nature is "all around us", humans have always used Nature's solutions to solve technical problems.

Humans have started the process of conscious design with the development of the first hand-axe about 20.000 years ago (French, 1994). In this first stage, the Nature has been used as a "tool" to improve the capabilities of humans to "prevail on it" in order to improve their living standards. This process has moved slowly but the observation of Nature in order to learn how to solve "technical problems" has been something that has characterized all the history of the humankind.

In the fifties of the last century, the possibilities given by the latest technologies i.e. production systems, new materials etc. have allowed scientists to use Nature as a model to be copied in order to realize technical reproductions of Nature's solutions (Bar-Cohen, 2006; Bhushan, 2009). This renewed interest in the use of Nature as a model has promoted this approach as a new field of Science (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006).

In the first evolutionary stages of the discipline, scientists were interested in "testing" the technologies to check if they were able in realizing technical versions of Natural systems. Literature is full of *ad hoc* examples of knowledge transfer from Biology to Technology but the selection of the Natural Source of Inspiration (NSoI) has been always leaved to the "chance", i.e. the Velcro® (De Mestral, 1961). Otherwise, biologists that have a personal interest in technology chosen a given NSoI, following a solution driven approach, can implement the Nature's solution in the technical domain individuating the correct problem to solve (Speck & Speck, 2008).

Nowadays, the use of Nature as a source of inspiration for the development of new technologies (Bar-Cohen, 2012b) cannot be leaved to the "chance". In fact in the last decades the scientific community has focused its research on the development of *Methods* and *Tools* for the Systematic *Use* of *Biological Information* (Lindemann & Gramann, 2004; Sartori, Pal, & Chakrabarti, 2010; Vattam, Wiltgen, Helms, Goel, & Yen, 2010; Vincent & Mann, 2002).

In these sixty years of science evolution were Nature's phenomena have been used as a solution for technical problems the names of this approach has changed several times e.g. Bionics (Harkness, 2002), Biomimetic (Vincent et al., 2006), Biomimicry (Benyus, 2002), Biologically-Inspired Design (Helms, Vattam, & Goel, 2009), etc.

Among all the approaches of using Nature as a source of inspiration the focus of this thesis is on the Bio-Inspired Design (BID) that is defined as an "[…] *approach to design that espouses the adaptation of a function and mechanism in biological sciences to solve Engineering Design problems* […]" (Vattam, Helms, & Goel, 2010).

The BID literature is rich and several tools, methods, and approaches have been developed from the scientific community.

One of the biggest limitations in the application of the Bio-Inspired Design is the need of biological knowledge in order to individuate the correct Natural Source of Inspiration (NSoI). Sometimes, also if the BID has been applied and the NSoI has been correctly individuated, there is an incomplete use of its problem solving potentiality due to the incomplete understanding of the biological system or phenomenon by the designer.

Moreover, there is a profound gap between the BID approaches and the available tools. In fact, all the methods developed by the scientific community share the same steps but none of them provides guidance for the designer in the use of these tools during the design steps.

Unfortunately, there are no strong connections between these approaches and the standard Product Development Process (PDP). This fact limits the application of the BID at the research field or in big companies that may have enough resources to invest in order to follow a completely new design approach.

Accepting the hypothesis that Nature's solutions can be a source of innovation in the product development process the main research question is the following:

How to systematically conceive a new Bio-Inspired Product?

This research question can be spited in three sub-questions that will be faced in the present thesis:

- *How a designer can be guided to use nature as a source of inspiration in order to solve technical problems?*

- *What is the industrial applicability of a method of problem solving based on the use of the tools currently developed by the scientific community for the BID?*
- *How these tools can be integrated into the product development process?*

This research is aimed at the integration of the most appropriate BID tools into a Problem-Solving Methodology that can be used by designers without Biological knowledge.

The target of this Problem Solving methodology are the Small-Medium Enterprises (SMEs) that usually have limited resources to invest in following or in developing completely new Design approaches. Furthermore, it has been decided to choose a target of young designers that are at the 2^{nd} or 3^{rd} Design experience and do not have any biological knowledge. At last, the methodology proposed is suitable for the development of products characterized by a level of complexity that ranges from 1 to 3. According to the classification proposed by (Hubka & Eder, 1988) that means *level 1* (i.e. Part, Component - Elementary system produced without assembly operations) to *level 3* (i.e. Machine, Apparatus, Device - System that consists of sub-assemblies and parts that perform a closed function).

The present thesis is divided in five sections. Section 1 concerns the State of the Art, and it is aimed at understanding the role covered by Nature in the concept development, focusing the attention in the use of Nature as a source of inspiration both in research and in industry. Furthermore, will be presented the tools used for representing the NSoI, the methods, and the methodologies that support the transfer of knowledge from Biology to the technical domain. At last some conclusions will be drawn.

Section 2 collects the original contribution of this work. After a synthetic description of the main features of the methodology's steps, it will be presented the methodology and the tools proposed for the correct application of each single step. These chapters are structured as follows: the proposed method, the proposed tools and a final section that explains the output features of the step*(i)* that will be the input for the subsequent step *(i+1)*.

In section 3, the methodology with the correlated methods and tools for each single step will be applied. A set of experiments with three main aims will be present. The first set of experiments will validate the use of the proposed tools by the intended target of designers. Then the Problem-Solving methodology will be entirely applied on 4 Test Cases about technical problems by a set of 3 designers in order to validate the ability of the method in guiding the designer in the development of the Bio-Inspired Product. Finally, with the last experiment on a second control group, the parameters chosen by the designers during the application of the method for the pre-selection of the NSoI will be validated.

Section 4 will show the results of the core experiments that are aimed at the methodology's validation. The validation is based on two main approaches:

A. <u>Ability</u> of the <u>methodology</u> to <u>guide</u> the <u>generation</u> of the <u>solution</u> - *Modified and improved approach from* (Coelho & Versos, 2010; Versos & Coelho, 1997)
    - *Presence of the "Nature's Solutions" in the conceptual solution*

- *Satisfaction of the requirements of multiple requisites*
- *Effectiveness of the method*

B. Fulfillment of the project requirements by the conceptual solution developed - (IEEE Standards Board, 1990)

   Validation: *Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled.*

At last, in the conclusions and future developments section the outcomes of this research activity will be discusses, highlighting to what extent the objectives have been satisfied, which limits has emerged during the testing phase as well as the further opportunities originated from this activity.

1 - Analysis of the State of the Art

This section aims at defining the context on which the whole research focuses. Furthermore, it also presents some considerations about the limitations that have emerged from the analysis of the various contributions on the methods and tools for the Bio-Inspired Design. The analysis of the SoA is divided in six sections.

In the first section, a brief description of the historical evolution of the approach of using the Nature as a model of study for technical purposes is presented. Then chapter two introduces briefly the features of the two most diffused Product Development Processes in order to present the frame in which the BID Problem-Solving Methodology will be inserted.

Section 3 is aimed at individuate the role of Nature in research, industry, and in the BID consultancy enterprises in order to understanding its use. Focusing the attention in the industrial interest and specifically on the design activities, section 4 presents the methods and the tools proposed by the scientific community in the BID research field.

In section 5 the conclusions about the analysis of the SoA will be presented, and based on these the section 6 presents the necessary hypotheses and the correspondent research questions.

1.1 - The evolution of the Bio-Inspired approaches

Humans have looked to Nature for inspiration for more than 3000 years since Chinese first try to make an artificial silk (Vincent et al., 2006). Leonardo, Vinci 15 April 1452 – Amboise 2 May 1519, studied birds flying to design flying machines. Unfortunately, Leonardo was not able to build his flying machines for the limits in the technologies available at that time. Another aspect of the failure of Leonardo's flying machines is correlated to the limits of his understanding of Nature, which are directly connected with to the limits of the technologies, the instruments, and the methods he used in his studies.

At a certain moment of the history of science, around the middle of the XX century, the need of a better understanding of Nature using physical sciences and vice versa, led the development of a new approach that has been called *Biophysics* (Harkness, 2002):

> *[…] is not so much a subject matter as it is a point of view. It is an approach to problems of biological science utilizing the theory and technology of the physical sciences. Conversely, biophysics is also a biologist's approach to problems of physical science and engineering, although this aspect has largely been neglected […]*

This approach of integrating Biology and Physical Sciences opened the way to the evolution of the Biologically Inspired Design as a new scientific discipline. Otto Schmitt, whose doctoral research was an attempt to produce a physical device that explicitly mimicked the electrical action of a nerve. By 1957, he had come to perceive what he would later label *Biomimetics* (Vincent et al., 2006).

During its evolution, the approach has assumed different names based on the specific type of application that it was dealing with. (Shu, Ueda, Chiu, & Cheong, 2011) present a synthetic list of names:

- **Bioengineering, Biological Engineering, Biotechnical Engineering:** Application of engineering principles and tools, e.g., physics, mathematics, analysis and synthesis, to solve problems in life sciences, and may involve the integration of biological and engineering systems.
- **Biomechanics:** Application of mechanical principles, e.g., mechanics, to study and model the structure and function of biological systems.
- **Biomedical Engineering:** Application of engineering principles and techniques to the medical field, e.g., design and manufacture of medical devices, artificial organs, limbs, etc.
- **Bionics:** Application of biological function and mechanics to machine design.
- **Biomimetics:** The 'study of formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones'.
- **Biomimesis, Biomimicry, Biognosis, Bioinspiration, Biomimetic Design, Bioanalogous design, Biologically Inspired Design**: Synonymous with *Biomimetics* to mean emulating natural models, systems, and processes to solve human problems.

Among all the terms, two of them became more famous of the others. The first is *Bionics* that have been used in the 1960 by Jack E. Steele from US Air Force during a meeting at Writh-Patterson Dayton, Ohio, to describe the science of systems which have some functions copied, imitated or learnt by Nature. However, the 1970s television series, Bionic Woman, about a human with electromechanical implants, also gives 'bionic' the connotation of 'biological + electronics,' or use of electronic devices to replace damaged limbs and organs (Shu et al., 2011).

The second name is *Biomimicry* because is in the title of a popular book by Janine Benyus (Benyus, 2002). This approach respect to the others gives it a connotation of sustainability and it is defined by the author as *"A conscious strategy by designers to observe and learn principles of design from nature".*

Indeed *Biomimicry* follows three paradigms (Benyus, 2002):

i. **Nature as model:** Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g. solar cell inspired by a leaf.
ii. **Nature as measure:** Biomimicry uses an ecological standard to judge the "rightness" of our innovations. After 3.8 billion years of evolution, nature has learned: *What works. What is appropriate. What lasts.*

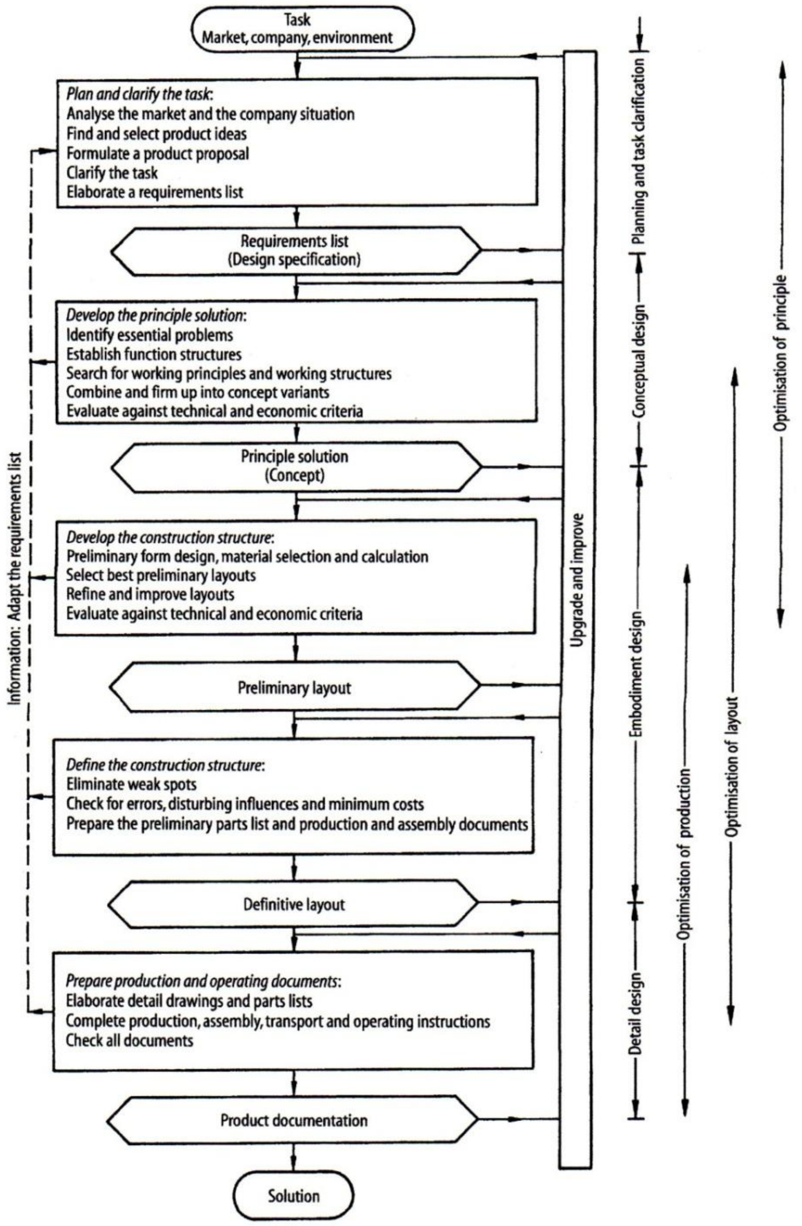
iii. **Nature as mentor:** Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can *extract* from the natural world, but what we can *learn* from it.

Finally a specific domain definition for Biologically Inspired Design or Bio-Inspired Design is given in (Vattam, Helms, et al., 2010):

"(…) is *approach to design* that espouses the *adaptation of a function* and *mechanism* in *biological sciences* to solve Engineering Design problems (…)"

All these approaches can be view as an interdisciplinary methodology for the transfer processes (Schmidt, 2008) of knowledge and information between Biology and Technology i.e. Engineering, Design and Engineering Design.

Figure 1.1 Steps in the Planning and Design Process (Pahl, Beitz, Feldhusen, & Grote, 2007)



1.2 - The Product Design and Development approaches

Each company adopts its own Product Design and Development (PDD) approach that can be either a specifically developed one or an adaptation of one of the standard approaches e.g. (Cross, 2000; Pahl et al., 2007; Ullman, 2003; Ulrich & Eppinger, 2012). Among the others, two PDD approaches are mostly diffused in terms of adoption in industry and of teaching at the university. One is the approach proposed by the German school of Design Engineering by (Pahl et al., 2007). The other is the one proposed by the American school of Product Design and Development by (Ulrich & Eppinger, 2012).

The Product Development Process proposed by (Pahl et al., 2007) is composed by 4 main steps:

I. Planning & Task Clarification
II. Conceptual Design
III. Embodiment Design
IV. Detail Design

The features of each step are synthetically depicted in Figure 1.1

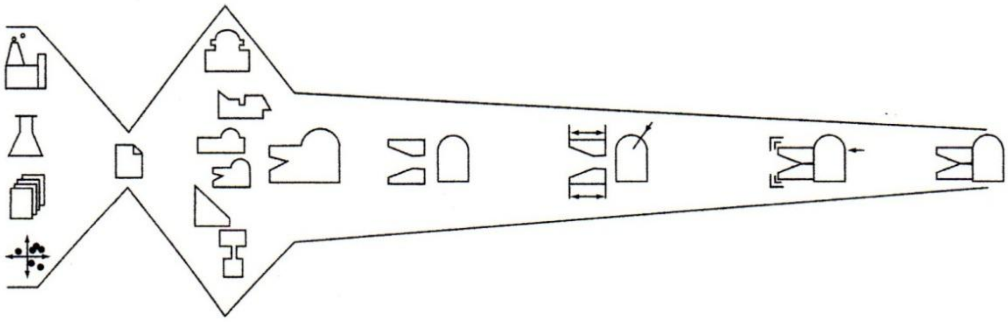
The approach proposed by (Ulrich & Eppinger, 2012) is composed by six phases:

I. Planning
II. Concept Development
III. System-Level Design
IV. Detail Design
V. Testing & Refinement
VI. Production Ramp-Up

A part the difference in the third phase’s names these two approaches share the first 4 steps. In the first one, the refinement can be done at different levels of detail in parallel to the other phases. On the other hand, the American approach foresees a specific stage of Testing and Refinement sequentially to the Detail Design.

The first stage of the Product Development (PD) is mostly related to the characteristic of the market and the type of products that the factory is developing. In this research due to the nature of the Bio-Inspired Design, the attention will be focused on the second step i.e. the Concept Development, which is shared in the two approaches. This decision will allow better understanding the common features and the possibilities to improve this stage in order to use Nature as a source of inspiration during the Design tasks.

Figure 1.2 The generic Product Development Process (Ulrich & Eppinger, 2012)



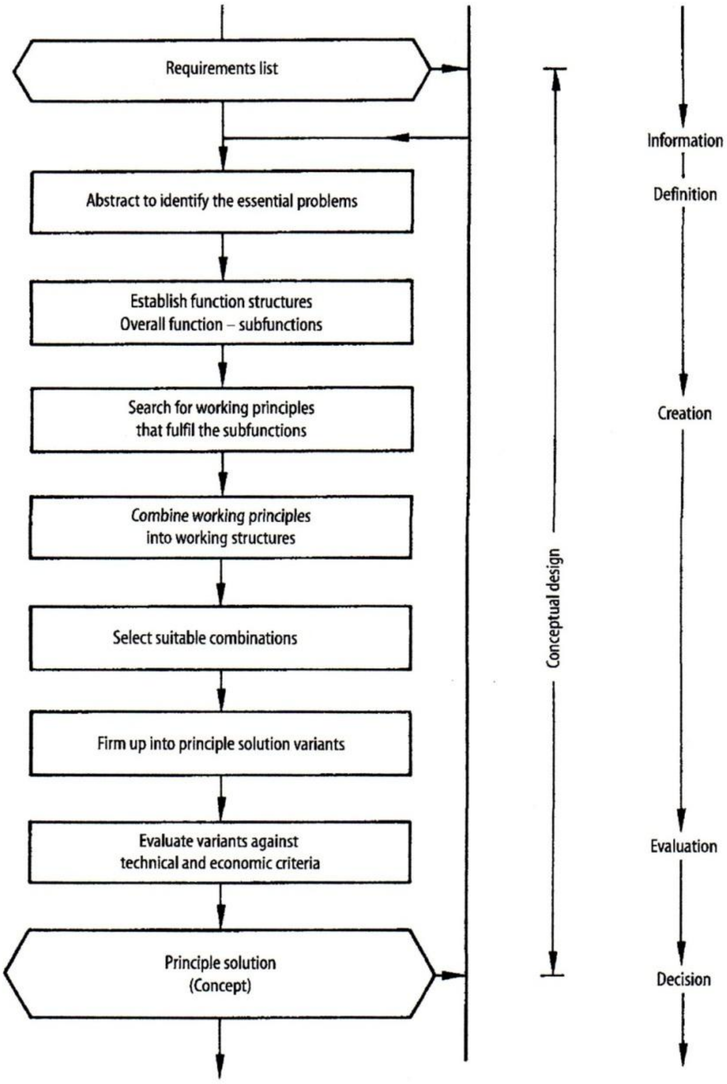
	Planning	Concept Development	System-Level Design	Detail Design	Testing and Refinement	Production Ramp-Up
Marketing	• Articulate market opportunity. • Define market segments.	• Collect customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family.	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design	• Consider product platform and architecture. • Assess new technologies.	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Develop product architecture. • Define major sub-systems and interfaces. • Refine industrial design. • Preliminary component engineering.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Test overall performance, reliability, and durability. • Obtain regulatory approvals. • Assess environmental impact. • Implement design changes.	• Evaluate early production output.
Manufacturing	• Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train workforce. • Refine quality assurance processes.	• Begin full operation of production system.
Other Functions	• Research: Demonstrate available technologies. • Finance: Provide planning goals. • General Management: Allocate project resources.	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues.	• Finance: Facilitate make-buy analysis. • Service: Identify service issues.		• Sales: Develop sales plan.	• General Management: Conduct postproject review.

1.2.1 - The Conceptual Design

(Pahl et al., 2007) define the Conceptual Design as the part of the design process where — by identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles and combining these into a working structure — the basic solution path is laid down through the elaboration of a solution principle. Conceptual design specifies the *principle solution*.

In Figure 1.3 presents the main steps proposed by (Pahl et al., 2007) for the stage of conceptual design.

Figure 1.3 Steps of the Conceptual Design (Pahl et al., 2007)

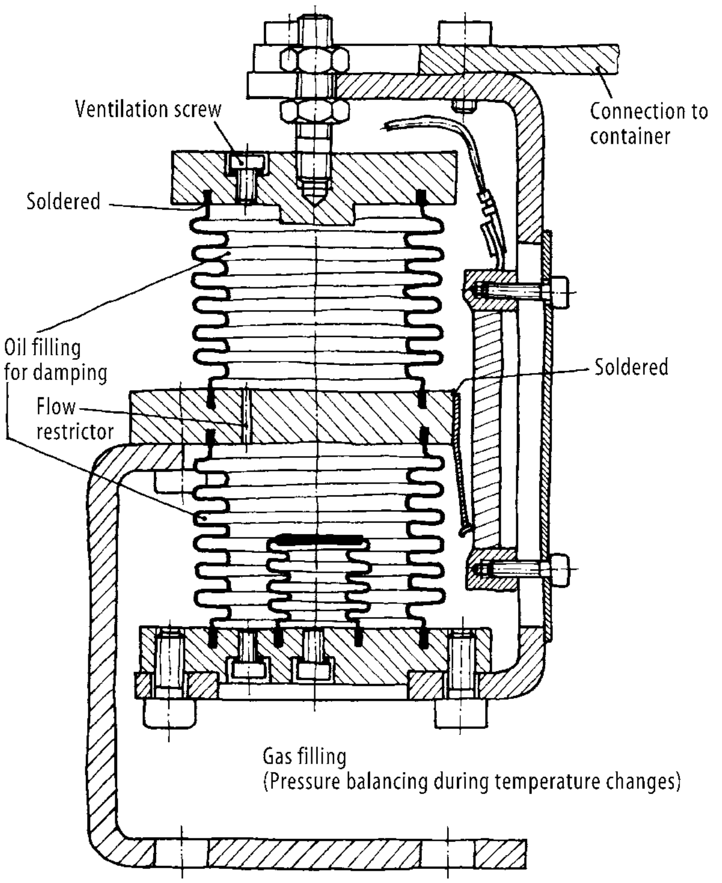


In the (Pahl et al., 2007) approach the principles are usually not concrete enough to lead to the adoption of a definite concept. This is because the search for a solution is based on the function structure, and so it is aimed, first and foremost, at the fulfilment of a technical function.

The *Sketch* that should be descriptive of *feasible working principles* represents the *principle solution*. Unfortunately, at this stage it is often not possible to assess the characteristics of a principle solution with quantitative data, particularly with regard to production and cost.

An example of these sketches is presented in Figure 1.4 that present only the main components that have a synthetic description of the main function or only the name if it is necessary in order to specifically define them. For example, there are no indications about the screws because at this level of detail there is no need of defining them completely in terms of features i.e. dimensions, fillet, length etc.

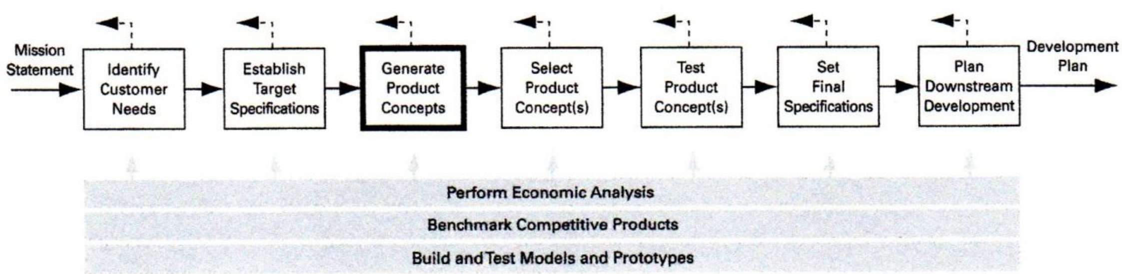
Figure 1.4 Principle Solution sketch (Pahl et al., 2007)



1.2.2 - The Concept Generation methods

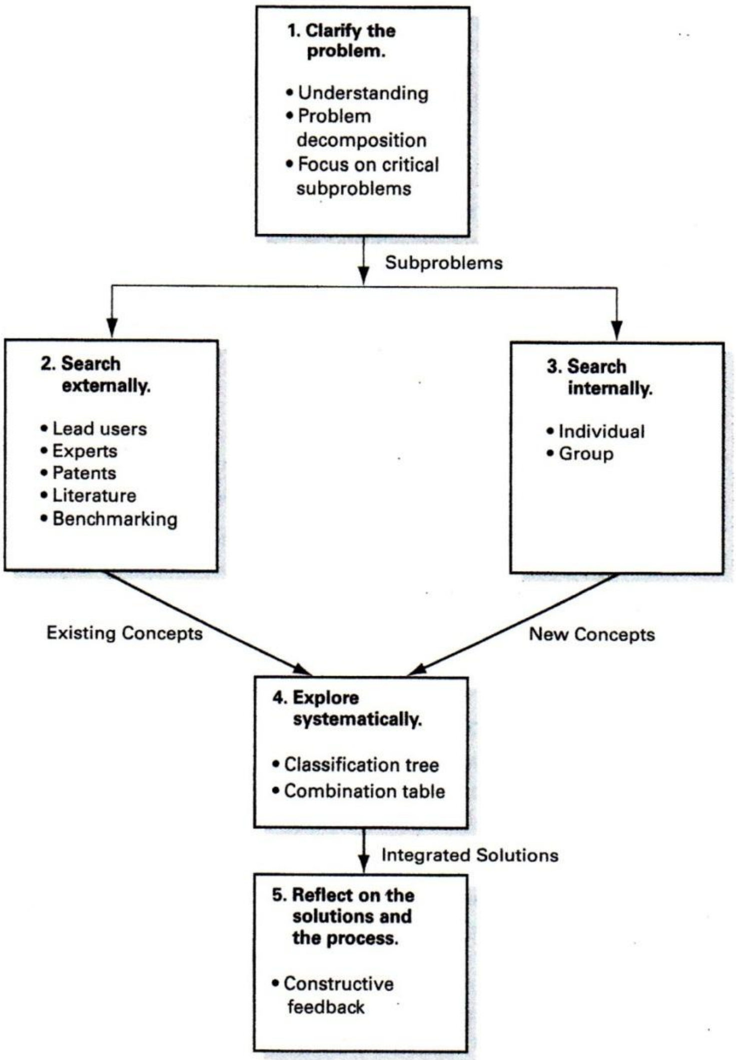
In the PDD by (Ulrich & Eppinger, 2012) the process is aimed at the generation of a set of concepts.

Figure 1.5 The Concept Generation in the Concept Development Phase (Ulrich & Eppinger, 2012)



In order to generate conceptual solutions the authors provide a Five-Step method. The method breaks a complex problem into simpler sub-problems. Solution concepts are then identified for the sub-problems by externally or internally search procedures. Classification trees and concepts combination tables are then used to systematically explore the space of solution concepts and to integrate the sub-problem solution into a total solution (Ulrich & Eppinger, 2012).

Figure 1.6 The Five-Steps Concept Generation method (Ulrich & Eppinger, 2012)



According to (Ulrich & Eppinger, 2012) a ***Conceptual Solution*** is defined as follows:

> *"[…] an approximate description of the **technology**, **working principles**, and **form** of the product […]"*

1.2.2.1 The External Search

The external search is aimed at finding existing solutions to both the overall problem and the sub-problems. The search is done by:

- Interview of lead users
- Consult experts
- Search patents
- Search public literature
- Benchmark related products

This search is fundamental for the information gathering and it is possible to gain some benefits:

i. Possibility to increase the knowledge about the problem
ii. Individuate already patented solutions
iii. Information on the strength and weakness of the competitors

1.2.2.2 The Internal Search

After having increased the knowledge about the problem with the external search, it is foreseen to carry on the internal search. During the internal search it is used the personal and team knowledge and creativity to generate solution concepts. Several methods can be applied but mostly the search is done by:

- Individual
- Groups

It follows that the search is aimed at finding out the knowledge of the company in order to solve a specific problem.

1.3 - The use of Nature as a Source of Inspiration

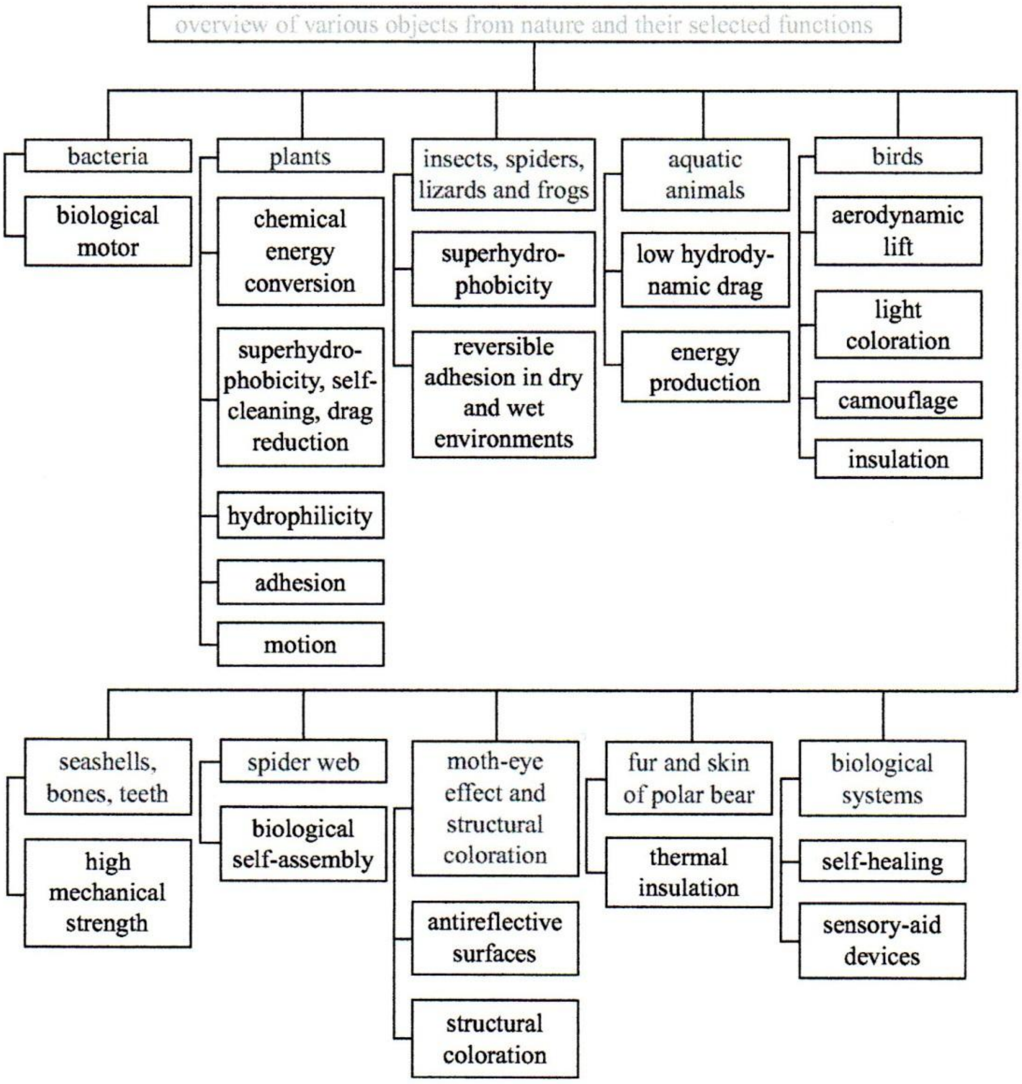
Nature have been always used as a model for mimicking and inspiring new technologies (Bar-Cohen, 2012b). Different fields of physical science have benefit by the knowledge that has been "borrowed" from Biology. Only to give an idea of the technologies that have been improved with the Nature's solutions hereafter is provided a syndetic list:

- Artificial Intelligence (AI)
- Smart system controls
- Artificial and Bio-Inspired materials and structures
- Senses and Sensors
- Artificial muscles and mechanism
- Etc.

Specifically several examples have been developed in the scientific community showing the way in which biological systems produce a range of functions which can be implemented in engineering, such as feedback-control of stiffness (muscles and nervous system), design of fault-free structures (trees) and damage-tolerant materials (wood) and high performance insulation (penguin feathers) and shock absorbers (hedgehog spines). (Vincent, 2006)

(Bhushan, 2009) gave a synthetic overview of the "Lesson" learnt from Nature in a comprehensive table of the biological objects and their selected functions.

Figure 1.7 An overview of the various objects from Nature and their selected functions (Bhushan, 2009)

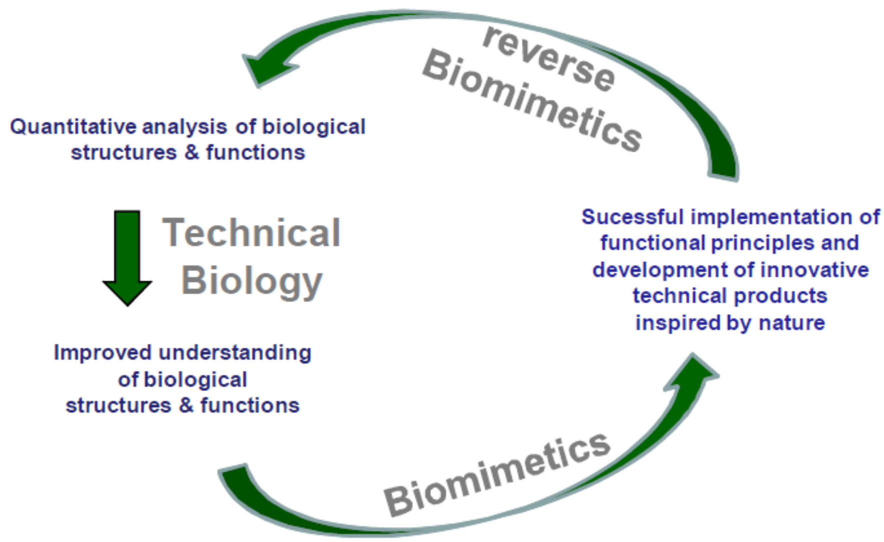


1.3.1 - Research Interests and Prototypes

Due to the interdisciplinary Nature of the Bio-Inspired Design (Schmidt, 2008) in research both Biology and Engineering increase their field of knowledge. Unfortunately there is a language barrier that is represented by the different languages (Schenkl, Kissel, Hepperle, & Lindemann, 2010) used by the two figures (Parvan, Oepke, Kaiser, & Lindemann, 2012). The collaboration between the disciplines generates new knowledge that increases the understanding of both the Natural phenomenon and the technical systems.

Thereby, Nature is a central topic in research. (Speck & Speck, 2008) present a schematic view of the relationship between the two disciplines and the results of their collaboration (Figure 1.8).

Figure 1.8 **Relation and model of operation of Technical Biology and Biomimetics** (Speck & Speck, 2008)



As opposed to the Leonardo's time, the technology has improved its capabilities at the point to be able to give the possibility to scientists to realize systems that mimic accurately Nature also in the smallest dimensional scales. Due to these new possibilities, one of the biggest interests for the technical side is that replicating the entire Natural system or phenomenon.

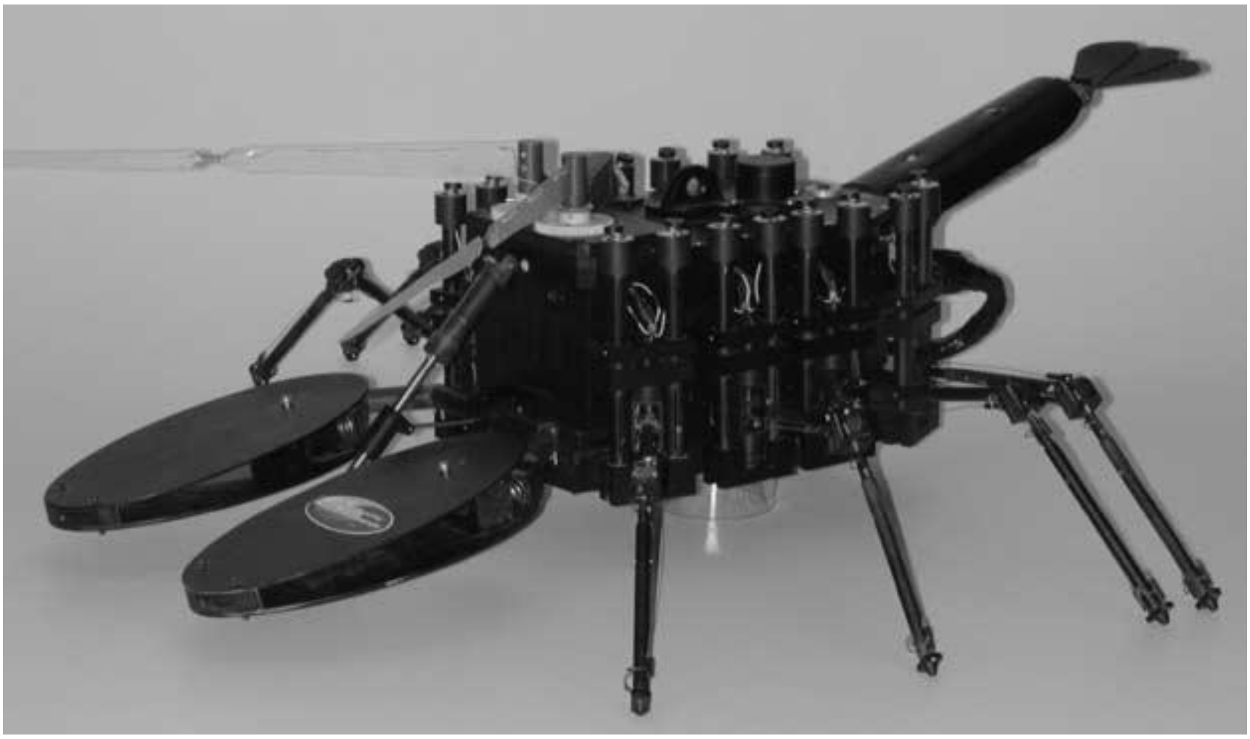
Natural mechanisms present tremendous important features for the nowadays challenges. A big interest of the research centres is the pure reproduction of the natural systems due to the use of the available technologies.

In the scientific literature is possible finding several examples of robots that are the copy of natural systems such as:

- Geckos (Menon & Sitti, 2005)
- Underwater walking animals (Ayers & Witting, 2007)
- Warms (Boxerbaum, Chiel, & Quinn, 2009)
- Octopus (Calisti et al., 2011)
- Fishes (Chu et al., 2012)
- Etc.

This systems are able to be inserted in hostile environments for applications such space exploration, military actions or natural studies without involving the use of humans which sometimes it is not possible such in March exploration or safe such in war or is a source of noise such in the study of fishes migration and movement.

Figure 1.9 The NU/DARPA/ONR lobster robot. The vehicle is based on a watertight electronics bay and associated battery pack. Actuators include eight three degrees of freedom legs, as well as claw- and abdomen-like hydrodynamic control surfaces. Motor-driven antennae are active flow surfaces (Ayers & Witting, 2007)



These prototypes, usually, are characterized by the use of materials, control systems, and production mechanisms that are the results of the front-end research and are not yet industrialized.

At the moment, these Bio-Inspired systems are still prototypes that are not yet industrialized due to the high costs and the low level of reproducibility of the systems. On the other hand, these applications are extremely important for the better understanding of natural phenomena and for pushing ahead the research boundaries in order to define new scientific challenges.

Due to this research, on the Technical Biology side of the scientific literature it is possible finding examples of studies dedicated at the understanding of the Natural phenomena using engineering approaches.

- Bird or bat: comparing airframe design and flight performance (Hedenström, Johansson, & Spedding, 2009)
- Biological implications of the hydrodynamics of swimming at or near the surface and in shallow water (Blake, 2009)
- Etc.

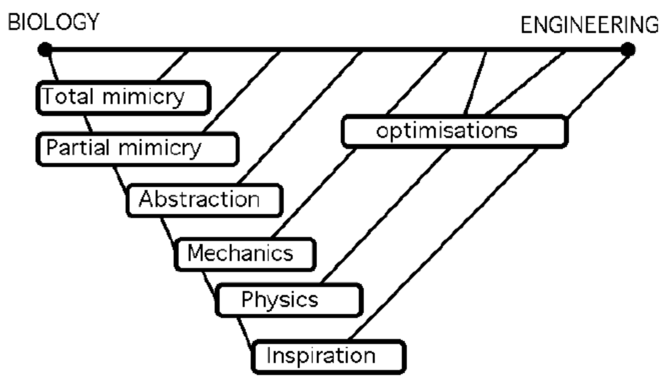
1.3.2 - Industrial Interests and Products

Day by day industries are showing a bigger interest in the results of the Bio-Inspired Design research. There are several levels of using Nature as a Source of Inspiration in companies. Some researches shows that it is extremely important give a “Natural soul” to the product in order to be more attractive for the market (Jasper, 2010).

Unfortunately, some companies use Nature only as a marketing tool in order to increase the appeal of their products. In fact, sometimes it is not possible to speak about Bio-Inspired Design because of that the NSoI is individuated *at posteriori.* This approach uses an NSoI, which sows analogous external features to the technical product, without really transferring the natural knowledge and probably missing some important features that could have the potentiality to improve drastically the design.

According to (Vincent, 2001) it is possible to execute a knowledge transfer between Biology and Engineering at different levels of abstraction.

Figure 1.10 A biomimetic “map” to illustrate the idea that the more abstract a concept is, the more adaptable it is within another discipline (Vincent, 2001)



Depending on the level of knowledge at which transfer will be done the design of the technical system will imply different levels of improvement on the final design.

1.3.2.1 Morphology, Shape and Function

The use of Nature as a source of inspiration in Industrial Design can be seen as an integration of the toolkit of the designer (Volstad & Boks, 2012). In this field, it is mostly diffused the use of *Natural Shapes* as a Source of Inspiration in the development of new products (Podborschi & Vaculenco, 2005).

In order to clarify the meaning of the word *shape,* according to the Oxford English Dictionary, is defined as follows (OED on Line, 2013):

> *[…] External form or contour; that quality of a material object (or geometrical figure) which depends on constant relations of position and proportionate distance among all the points composing its outline or its external surface; a particular variety of this quality. […]*

To be able in gaining knowledge about the Shape of Natural systems and phenomena is necessary find out if there is a field of biology interested in the study of these features. In fact, biologists have been always interested in the study of these characteristics of the natural systems and according to the Oxford English Dictionary in Biology, *Morphology* is defined as follows (OED on Line, 1872):

> *[…] The branch of biology that deals with the form of living organisms and their parts, and the relationships between their structures. Formerly: spec. the comparison of the forms of organisms and their parts in order to identify homologous structures. […]*

Analyzing the above-mentioned definition, is possible to say that morphology studies three different aspects of Natural systems:

- Form
- Parts
- Relationships between their structures

The definitions shows clearly that in natural systems the study of the shape is characterized by the relation of more features of the system and it is important to deepen the understanding of it in order to explain why the system has this particular shape instead of another one.

Several designers use objects' shapes as a creative language for their products and this is an extremely important aspect of the design.

In one of the most important publications in the Industrial Design field, (Munari, 1963) says:

> *[…] L'arancia quindi è un oggetto quasi perfetto dove si riscontra l'assoluta coerenza tra forma, funzione, consumo […]*

The translation provided by the author is the following:

The orange, therefore, is a perfect object in which the absolute coherence of form, function and consumption is found.

This quote shows a profound relation between the shape and the function in nature, moreover Jean-Baptiste de Lamarck (Bazentin-le-Petit, 1st August 1744 – Paris, 18 December 1829) said that:

> *[…] Form follows function […]*

Looking at the concepts of two of the most important Designers in the field of Bio-Inspired Design such Luigi (Lutz) Colani and Jean-Marie Massaud it is possible to find a confirmation of the above-mentioned quote.

Starting from the analysis of the work of Luigi Colani, its concepts show clearly his passion for the speed. During his entire carrier he has designed innovative shapes for every type transportation system e.g. cars, motorcycles, trains, camions etc.

Figure 1.11 F1 Eifelland 1972 designed by Luigi Colani – Pilot Rolf Stommelen

He used extremely innovative shapes characterized by an exasperated level of roundness. It is possible to conclude that behind his work there is a clear relation between shapes and function that allows to take advantage of the maximum aerodynamic efficiency available in nature.

Figure 1.12 A track designed by Luigi Colani

Unfortunately, there is not explicit and released information from Colani about the specific shapes from Nature that he used in the designs.

On the other hand Jean-Marie Massaud has given the name of the NSoI that he have used during the design to one of its most famous and innovative projects i.e. the White Whale of the Skies that is a Luxury Airship which lets Tourists Enjoy the High Life (Blinda, 2008)

Figure 1.13 White Whale of the Skies designed by Jean-Marie Massaud – side view

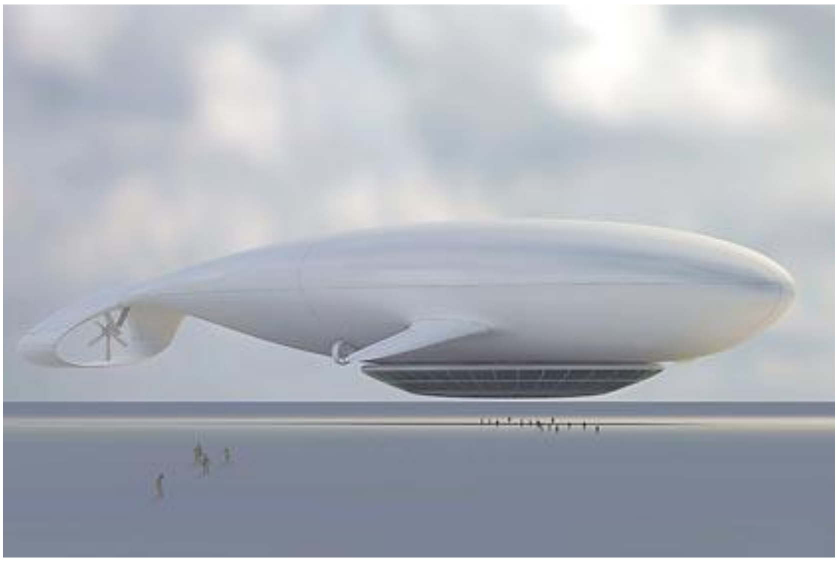


Figure 1.14 White Whale of the Skies designed by Jean-Marie Massaud – rear view

The design of the whale-shaped airship is a *futuristic Moby Dick that is actually an airship containing a luxury hotel. Guests of the "Manned Cloud" will be able to enjoy the world's most beautiful sights from up on high.*

Here the entire function of the system has no connections with the one can be attributed to the whales. In any case, in the Bio-Inspired Design there is a clear functional connection. Indeed, analyzing the needs of the system it is possible to deduce the need of containing a huge amount of helium in its "body".

In fact, the project that has been developed in collaboration with the ONERA the aerospace France center is an evolved version of the zeppelin that uses the most efficient shape in nature. In this case, it has been chosen the whale that is well known to be one of the biggest creatures in nature that still has a great hydrodynamic efficiency.

The relation between the shape and the function can be found in the high level of the system's capacity having good aerodynamic efficiency.

Figure 1.15 White Whale of the Skies designed by Jean-Marie Massaud – Travelling render

According to (Podborschi & Vaculenco, 2005) there is no shape without function in nature, as well as function without shape.

1.3.2.2 Industrial products

One of the first Bio-Inspired Products developed in industry as a mass product has been the Woodpecker Bionic Ice Tool by CAMP. *The Woodpecker Ice-Tool is based on the laws of nature* as advertises the brochure (CAMP, 1993). The product is a combination of three NSoI all in the same system in order to solve several problems related to the tool (Lodato, 2005)

The first feature of the system that is visible is the double S *shape* taken by the woodpecker. However, looking more in detail it is possible individuate that both the structure of the handle and the connecting point of the hammerhead are studied in to reduce the vibrations. Furthermore, the grip of the handle's grip has been incremented using the surface characteristic of the sharkskin.

Comparing Figure 1.16 and Figure 1.17 it is possible to see how the use of Nature as a source of inspiration has been stressed for the advertisement. First, has been chosen a bolt with a shape that explicitly remembers the eye of the woodpecker. The bolt, chosen for the advertisement, is not congruent with the function of easily change of the front part of the hammerhead in case of failure. This feature has been presented as an advantage for the Bionic Ice-Tool in the brochure and can be recognize for the presence of a key in the industrialized version of the product.

Second, it has been chosen an insert for the rear part of the hammer that has a shape with proportions much more similar to the tail of the animal respect to the one of the industrial product.

Figure 1.16 Advertisement picture of the Woodpecker Ice-Tool (CAMP, 1993)

Unfortunately, the product has been a complete failure in the market for several problems especially correlated with the wrong shape of the handle. The lower shape of the handle present the problem that puts the hand of the mountain climber too near to the ice wall and can happen that during the percussion he or she can slam the fingers.

Figure 1.17 Industrialized version of the Woodpecker Ice-Tool by CAMP

A detailed analysis of the NSoI and the technical product proposed in (Cappelletti, 2013) has shown that the Natural system features have not been completely understood by the designers.

More detailed studies on the features of the Woodpecker (Vincent, Sahinkaya, & O'Shea, 2007; Yoon & Park, 2011), which has been the major NSoI for the development of the BIP, allowed other designers to better understand the Natural system and implement different solutions using the same NSoI.

In the first example a conceptual solution for a woodpecker hammer has been realized by (Vincent et al., 2007). In this solution it is used the behaviour of the body of the woodpecker and not only the external shape allowing to individuate the best position for the centre of rotation of the hammer in order to improve the penetration capabilities.

Another extremely important feature of the woodpecker is the ability of shock absorbing of his head that protect the brain allowing the animal to do not become crazy during the percussions. (Yoon & Park, 2011) present a system to protect electronic components during an impact. The system uses a combination and the sequence of the material that create i.e. the structure of the bone of the woodpecker. In this case, the materials are an equivalent technical version in term of feature of organic ones.

The second noteworthy example of a Bio-Inspired Industrial Product has been recently provided by the DUNLOP sport. In 2009 Dunlop has developed an entire line of rackets and the correlated accessories named BIOMIMETIC Series.

In this example, there is a change in the industrial approach, where the shape is not the main feature of the Bio-Inspired Product. In these products, it is not possible to individuate the NSoI just by giving a look to them if there is not an explicit advertisement that recalls the connection between the Natural Source of Inspiration and the Bio-Inspired Product.

The aim of the design is improving the rackets' performance by the use of Natural Knowledge both in the external features and in the structural characteristics.

For the first time for a BIP has been given quantitative values of performance increment by the adoption of Natural knowledge (http://www.dunlopsport.com/gb/technology/tennis):

- Aeroskin:
  Inspired by the skin of the shark reduces aerodynamic drag by up to **25%*** for increased racket speed and power.
- Gecko-Tac:
  Inspired by the morphology of the pads of the gecko's foot provides up to **50%* more grip** and tack than previous Dunlop technology, giving greater control, feel and precision.
- HM6 Carbon:
  Inspired by the honeycomb structure reduces racket frequency and vibration by up to **10%*** for ultimate energy return and feel.

Figure 1.18 Fernando Verdasco – Dunlop BIOMIMETIC Racket Series 300

Finally, the last industrial case is related to the aerospace industry. AIRBUS expresses its interest in the use of Nature as a Source of Inspiration saying that they are improving several aspects of their aircrafts using Nature's solutions. From (http://www.airbus.com/innovation/eco-efficiency/design/biomimicry):

> *[…] A growing number of aeronautical innovations have been inspired by an array of natural structures, organs and materials – and these tried and tested patterns of the natural world will continue to be a powerful source of inspiration in the future. […]*

1.3.3 - Consultancy Enterprises

Beside to the attention expressed by the research world and from industry, nature is extremely interesting also for the consultancy enterprises.

Among the others, it has been decided to describe the BIOMIMICRY 3.8 and the Bio-TRIZ ltd. The former is the biggest Bio-Inspired Design consultancy in the world that serves clients such as NIKE, Levi's, UNEP, IDEO etc. The latter is a small enterprise that is created by a family business where the two members are an Engineer and a Biologist. Also with this small dimension, Bio-TRIZ has served important customers such PHILIPS and the ESA (European Space Agency).

These two examples represent the upper and the lower limit of the Bio-Inspired consultancy enterprises. Anyhow, also if they serve different clients both in dimension and in need therefore the consultancy enterprises have the need to individuate the biggest number of Natural Sources of Inspiration, classify them, and make it usable the highest number of times in order to survive in the market and make business.

Even though the founder scientists of the two companies, in past have followed a common approach, the database of natural phenomena, they have evolved separately following different paths. The two enterprises for their clients have developed two different tools with specific features.

1.3.3.1 A Database of Natural Strategies – AskNature.org

BIOMIMICRY 3.8 is composed by two organizations, the first one is the consultancy and the second is a non-profit organization called BIOMIMICRY INSTITUTE 3.8. One of the projects of the BIOMIMICRY INSTITUTE 3.8 is the database AskNature.org that is used and fueled with new NSoI by the designers, the biologists, and the engineers that work in the consultancy.

The database is a collection of Natural phenomena classified following the BT - Biomimicry Taxonomy (Biomimicry Institute, 2008). The Biomimicry Taxonomy is a classification system for organizing the information on AskNature.org about **how organisms meet different challenges** (http://www.asknature.org/article/view/biomimicry_taxonomy).

The Biomimicry Taxonomy is three hierarchical levels:

- Group
- Sub-group
- Functions

Each entry of AskNature.org is a strategy. The strategies are potential solutions to these challenges. For example, the challenge and Biomimicry Taxonomy of an insect's strategy might be as follows:

- <u>Insect's challenge</u>
  Protect itself from animals that want to eat it.
- <u>Strategy</u>
  Anti-reflective eyes to avoid detection in moonlight via nanoscale protrusions on the eyes' surfaces (http://www.asknature.org/article/view/biomimicry_taxonomy).

Biomimicry Taxonomy:

- GROUP: Maintain health
- SUB-GROUP: Protect from biotic factors
- FUNCTION: Protect from animals
- STRATEGY: Nanoscale protrusions

In Figure 1.19 is reported a screenshot of the strategy page of the above-mentioned Natural Phenomenon.

Figure 1.19 Anti-reflective eyes to avoid detection in moonlight Strategy Page on AskNature.org

For each challenge, in the page there is a set of information:

- Summary
- Excerpt
- Scientific name of the organism
- Bio-Inspired products and application ideas
- Experts
- References

The database is freely accessible and can be browse both by names and by categories (Natural Functions).

1.3.3.2 A Matrix of Natural Solutions

The two scientists behind the Bio-TRIZ ltd, Olga Bogatyreva and Nikolay Bogatyrev, have worked in a project for the development of a database of Natural Phenomenon. These Biological systems have been classified using the TRIZ Theory (Vincent, Bogatyreva, Pahl, Bogatyrev, & Bowyer, 2005).

Starting from this project, all the information about the Natural systems have been analysed on a higher level of abstraction. They have analysed some 500 biological phenomena, covering over 270 functions, at least three times each at different levels of hierarchy. In total, they have analysed about 2500 conflicts and their resolutions in biology, sorted by levels of complexity. This analysis allowed the authors to abstract and categorize Biological systems by the generalized engineering problems that can be solved by Biology. The Bio-TRIZ ltd is not interested in the creation of a collection of natural phenomena but in the identification of some natural Design Paths.

It is proposed a six fields of operation in which all actions with any object can be executed: substance, structure, energy, information, space, and time. These six operational fields re-organize and condense the TRIZ classification both of the features used to generate the conflict statements and the inventive principles. Then it is considered a modified version of the conflict matrix from TRIZ that is constructed from these fields Table 1.1.

Table 1.1 Matrix derived from the standard TRIZ 39x39 matrix

fields	substance	structure	space	time	energy	information
substance	6 10 26 27 31 40	27	14 15 29 40	3 27 38	10 12 18 19 31	3 15 22 27 29
structure	15	18 26	1 13	27 28	19 36	1 23 24
space	8 14 15 29 39 40	1 30	4 5 7–9 14 17	4 14	6 8 15 36 37	1 15–17 30
time	3 38	4 28	5 14 30 34	10 20 38	19 35 36 38	22 24 28 34
energy	8 9 18 19 31 36–38	32	12 15 19 30 36–38	6 19 35–37	14 19 21 25 36–38	2 19 22
information	3 11 22 25 28 35	30	1 4 16 17 39	9 22 25 28 34	2 6 19 22 32	2 11 12 21–23 27 33 34

This more general TRIZ matrix is now used to place the inventive principles of TRIZ into a new order that more closely reflects the biological route to the resolution of conflicts. The authors called this new matrix BioTRIZ Table 1.2.

Table 1.2 Bio-TRIZ matrix derived from biological effects

fields	substance	structure	space	time	energy	information
substance	13 15 17 20 31 40	1–3 15 24 26	1 5 13 15 31	15 19 27 29 30	3 6 9 25 31 35	3 25 26
structure	1 10 15 19	1 15 19 24 34	10	1 2 4	1 2 4	1 3 4 15 19 24 25 35
space	3 14 15 25	2–5 10 15 19	4 5 36 14 17	1 19 29	1 3 4 15 19	3 15 21 24
time	1 3 15 20 25 38	1–4 6 15 17 19	1–4 7 38	2 3 11 20 26	3 9 15 20 22 25	1–3 10 19 23
energy	1 3 13 14 17 25 31	1 3 5 6 25 35 36 40	1 3 4 15 25	3 10 23 25 35	3 5 9 22 25 32 37	1 3 4 15 16 25
information	1 6 22	1 3 6 18 22 24 32 34 40	3 20 22 25 33	2 3 9 17 22	1 3 6 22 32	3 10 16 23 25

Using the Bio-TRIZ matrix, the consultants are able to solve technical problem by searching for the correspondent Biological problem at an abstract level that have been described as a contradiction in the matrix and uses the correct Biological solution for the given technical problem.

1.4 - On the use of Natural knowledge for designing

According with the analysis of the SoA presented, it is possible to say that there is a real interest for the use of *Nature's solutions* as a source of knowledge and information to improve the design of technical products.

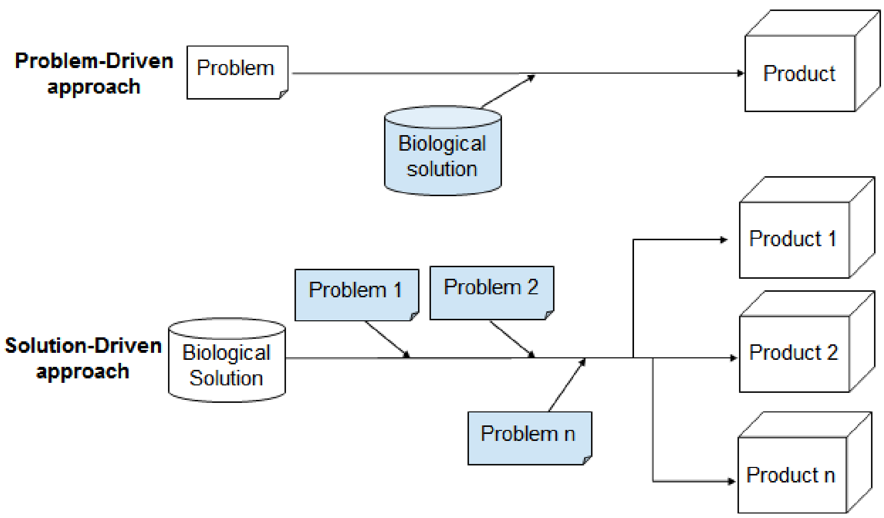
First of all, it is fundamental to note that Biologists have a complete different purpose when they describe a natural phenomenon. It follows the need in individuating the ways and the tools that can allow designers to individuate, understand, and extract the Natural knowledge that is necessary for design purposes.

Depending on the Design task and the NSoI's individuation strategy, two main approaches can be distinguished i.e. the Bottom-Up process and the Top-Down process (Speck & Speck, 2008). In the former, new Bio-Inspired Design projects sprout from new and promising results of fundamental Biological research. On the other hand, a Bio-Inspired Design that follows the Top-Down process typically starts with the work of technicians. In this approach, improvements in the body of natural knowledge are sought for already existing technical products o new designs.

According to (Schenkl, Kaiser, & Lindemann, 2011) these two approaches, if we look into the problems and solutions space, can be called respectively Solution-Driven and Problem-Driven approach.

In the Solution-Driven approach, it is individuated a Nature's solution and then several problems can be solved thanks to its use in order to develop several products.

Figure 1.20 Problem-Driven approach and Solution-Driven approach for BID (Schenkl et al., 2011)



The Problem-Driven approach starts from the technical problem and individuates the most appropriate NSoI that solve(s) the specific problem(s) in order to lead the development of a new Bio-Inspired Product.

1.4.1 - The search for the Natural Source of Inspiration

According to the followed approach i.e. Problem-Driven or Solution-Driven, different features characterize the search phase of the Natural Source of Inspiration (NSoI).

For the Solution-driven approach, it is possible to say that there is almost no search phase in order to individuate the most appropriate NSoI. Following the path, Solution-to-Problem the designer starts with a particular “Biological Solution” in mind. The search phase is shifted on the last phase of the approach where it is searched for a problem to solve. It is important to note that this type of search may also include define entirely new problems (Helms et al., 2009).

On the other hand, following the path Problem-to-Solution i.e. the Problem-Driven approach, the search for the NSoI results one of the most difficult parts of the entire procedure. Due to the number of Natural systems and phenomena, the search can have a tremendous amount of results. Because the Designers have usually a lack of knowledge about natural organisms, sometimes it is extremely difficult individuating a suitable Source of Inspiration in order to solve the technical problem.

In order to solve this problem several approaches have been developed by the scientific community. For example a bridging terminology for Bio-Inspired Design that allows Designers developing an Engineering-to-Biology thesaurus (Chiu & Shu, 2005; Nagel, Stone, & McAdams, 2010). Or, the insertion of metadata in Natural-Language corpora such as part of speech that allows to create a Natural-Language approach to improve the NSoI search phase (Ke, Shu, Wallace, & Chiu, 2010; Shu, 2010). Moreover, it has also been proposed a technical functional grammar oriented to Bio-Inspired Design (Rosa, Rovida, Viganò, & Razzetti, 2011) or a search based on symbols (Wei, Guozhong, Hui, & Runhua, 2013).

As pointed out in section 1.3.1 - Research Interests and Prototypes, the intersection between physical sciences and Biology creates a new corpus of Knowledge where Biological systems and phenomena are analyzed, studied and explained with scientific tools. This new Natural Knowledge corpus, already suitable for design purposes can be searched in two main categories:

- BID Scientific publications
- Collection of Natural Phenomena for Design purposes

1.4.1.1 Books and Scientific papers

Due to the features of the BID scientific literature i.e. the scientific and/or technical description of the natural systems and phenomena, it is possible to individuate suitable NSoI also without the support of a Biologist. During the search phase there is still the possibility to search in a portion of the literature that create a bridge between the two disciplines i.e. Physical Sciences and Biology.

This literature is composed by:

- **Books** e.g. (AA.VV., 2010, 2011, 2013; Bar-Cohen, 2006, 2012a; Hill, 1997)

  Which are collections of Bio-Inspired Products & Prototypes subdivided by technological categories.
- **Journals**
  - *Journal of Bionic engineering*
  - *Bioinspiration & Biomimetics*
  - *The Journal of Experimental Biology*

  These journals contain information, structured in the standard scientific way, about Bio-Inspired Solutions and scientific studies of natural systems.

In the recent past, there has been an attempt of classifying the Journal papers about BID, by an Online Team Collaboration i.e. the PB-Works, aimed to capture knowledge, share files, and manage projects. PB Works did the attempt (http://biomimetic.pbworks.com/w/page/14811914/FrontPage). The classification has been done thanks to the use of a set of parameters in function of the scale of the phenomena. Using these classification criteria it has been realized a Biomimetic Technology Tree:

Table 1.3 Biomimetics Technology Tree – PB Works

Biomimetics Technology Tree		Scale									
		2.2-2.6 nm	0.3-300 nm	5-10nm	5-20µm	2-20 mm	8mm-30cm	50cm-9.1m	10nm-83.8m		
		DNA	Macromolecule	Organelle	Cell	Tissue	Organ	System	Organism	Population	Ecosystem
Structures and Materials	Structures				[41]	[12] [13] [15] [31] [39] [49]	[72]		[1] [29] [43] [69] [71] [84] [100] [101][105] [149] [176] [200]		
	Materials		[154] [167] [173] [175]			[14] [16] [17] [18] [20] [118] [156]			[2] [32] [38] [47] [48] [63] [75] [76] [95] [158] [203] [204]		
Mechanisms and Processes	Mechanisms				[61]	[136] [159]	[10] [51] [97] [155] [170] [171]	[99] [178]	[3] [5] [6] [7] [8] [9] [21] [24] [25] [26] [27] [28] [30] [36] [37] [45] [50] [52] [53] [54] [55] [56] [57] [59] [60] [64] [65] [66] [67] [70] [74] [77] [78] [79] [80] [83] [86] [88] [91] [93] [94] [96] [98] [102] [103] [104] [106] [107] [108][109] [113] [114] [127] [137] [144] [145] [153] [157] [160] [161] [162] [164] [165] [168] [177] [186] [187] [188] [190] [193] [195] [199]		
	Processes								[23] [85] [92][116] [142] [152]	[62][110][112]	
Behavior and Control	Behavior	[126]			[179]			[117]	[22] [34] [81][123] [129] [132] [139] [140]	[33] [46] [120] [121] [122] [124] [125] [128]	[131]
	Control					[134]	[35][82]	[183]	[4] [58] [87] [111] [130] [146] [148] [150] [151] [166] [172] [174] [184] [197] [201]	[169]	
Sensors and Communication	Sensors		[205]		[68]		[192] [196]	[163]	[11] [19] [40] [42] [44] [90] [119] [141] [143] [180] [182] [185] [191] [194] [198] [202]		
	Communication							[181]	[138] [147]	[73] [133]	
Generational Biomimicry	**Generational**								[89][115] [135]		

Each entry of the cell is a number that is a direct link to a correlated scientific paper about the Natural Phenomenon. The paper(s) describe the Natural system that performs a specific task within a given dimensional scale.

1.4.1.2 Database of Natural Phenomena

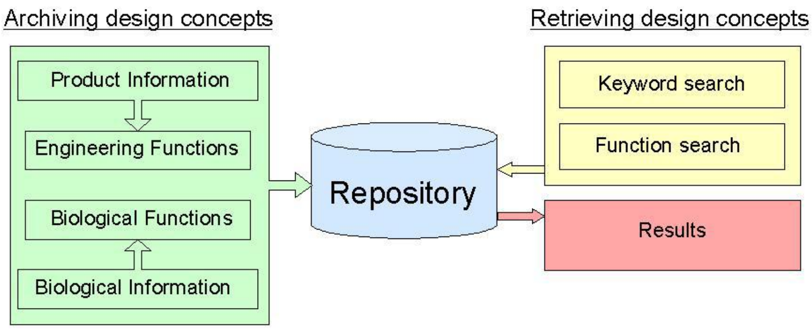
After the study of the Natural Systems, the information gained about the phenomenon can be reworked and structured into a database according specific descriptive criteria. This approach have been followed by different authors such as (Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005; Rosa et al., 2011) that have developed a software to store and collect example of Natural systems described via functional and causal models.

Starting from the work proposed by (Vincent et al., 2005) it has been developed the first version of an on-line collection of NSoI for design purposes. The project supported by the European Space Agency, in the first years of 2000, developed the database **BIONICS2SPACE** database (DB) that was a collection of natural effect classified by their function. The aim of the project was helping the designers of the ESA in the development process of new Bio-Inspire Space systems by giving a collection of NSoI stored in a DB.

Figure 1.21 BIONICS2SPACE Database of Natural Phenomenon for Design Purposes

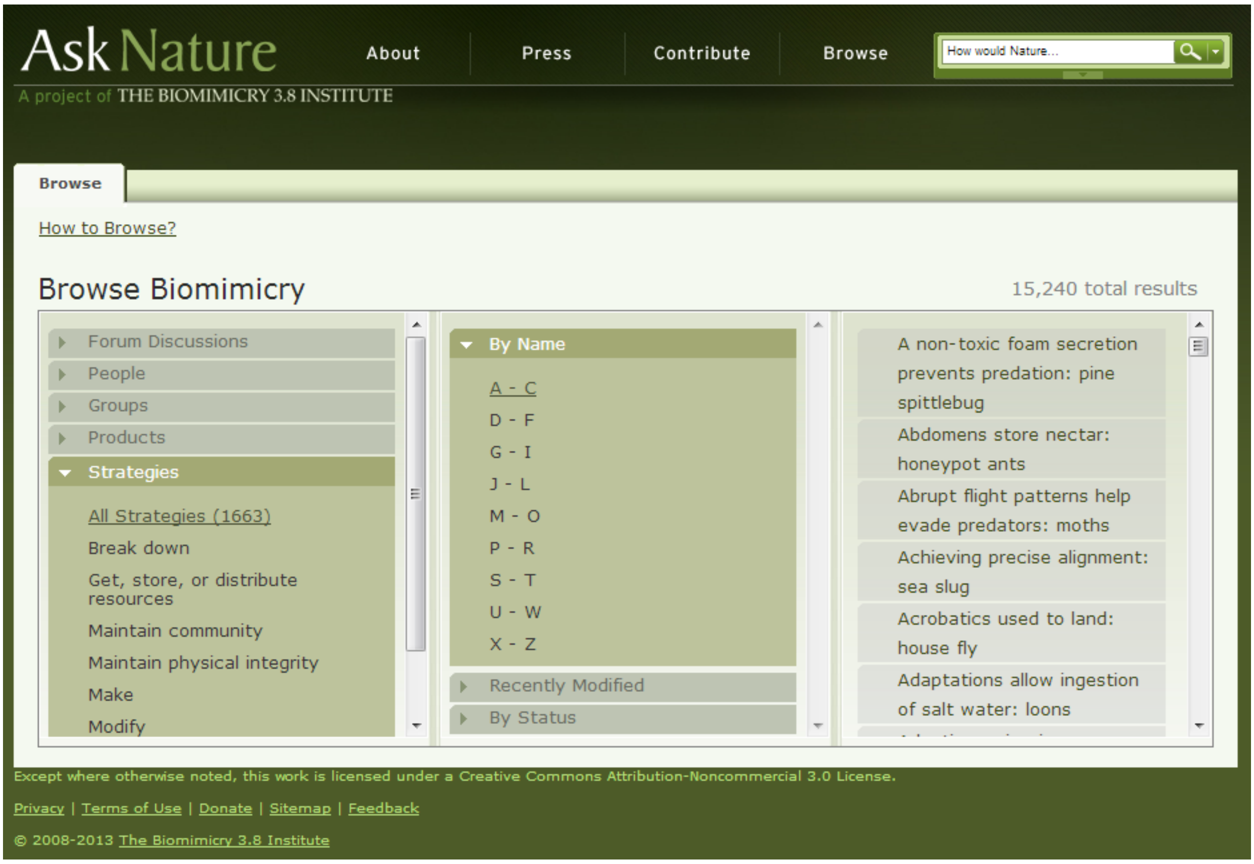
A further example of the same approach arose from the work proposed by (Golden, 2005) at the University of Maryland. In Figure 1.22 it is represented the main idea behind the repository.

Figure 1.22 Archiving and retrieving Design Concepts (Golden, 2005)



Starting from this project the BIOMIMICRY INSTITUTE 3.8 acquired the structure proposed by (Golden, 2005) and with some improvements it has been transformed in the main project of the BIOMIMICRY 3.8 INSTITUTE i.e. the AskNature.org Database of Natural Strategies.

Figure 1.23 **A screenshot of the AskNature database of Natural strategies (http://www.asknature.org/browse accessed on 31/12/2013)**



A team of experts, mostly biologists, daily updates the database so the number of the examples is continuously growing.

The database is meant to be browsed mostly in two ways:

- Keywords
- Strategies

Nevertheless, depending on the type of information that the designer is looking for, the DB give the opportunity to be browsed in several ways.

1.4.2 - The representation of the Natural Source of Inspiration

The use of models leads to a structured representation of the knowledge about Natural systems. Models are an important instrument for the understanding of the biological phenomenon both for biologists and for designers (Vincent, 2003). In order to improve the communication path between the disciplines

(Schenkl et al., 2010) it is important to individuate the correct models from both Biology and Engineering (Farzaneh, Kaiser, & Lindemann, 2013).

1.4.2.1 Biological models

According to the work of (Farzaneh et al., 2013) Biologists do not use models to describe the Natural phenomenon in the scientific publication of their field of study. They use models such as graphs and data matrix in order to show the numerical results of their study but not to explain how the Natural system works. On the other hand, they use models of various kinds to describe the behaviour of a system, the relation of it within the environment etc. in the text books used in the first years of the course in Biology.

These models, retrievable in the above-mentioned books, describe six different properties. (Farzaneh et al., 2013) propose the following classification:

- **Relational property:**
  The model represents relations between several biological systems or system elements
- **Change property:**
  The model represents the change of a biological system or sys-tem elements
- **Morphological property:**
  The model represents the morphology of a biological system, i.e. the shape and/ or relations of its elements
- **Comparative property:**
  The model represents a comparison between several variations of biological systems or its elements
- **Data property:**
  The model represents data acquired about a biological system or its elements
- **Mathematic property:**
  The model is a mathematic representation of a biological system or its elements

Unfortunately, there is not a standard format for the classis of the models proposed in (Farzaneh et al., 2013). In fact the models can describe more than one property and can have different morphologies in terms of type of information, type of representation, type of images used etc.

1.4.2.2 Technical models

In engineering the functional modelling is a broadly diffuse approach to describe technical systems (Pahl et al., 2007). In the scientific literature several approaches exist for functional modelling (Eisenbart, Blessing, & Gericke, 2012). In engineering, one of the most diffused models used to describe the Function, the Behaviour, and the Structure that is called FBS and has been proposed by (Gero, 1990) has been constantly evolved and refined during the years (Dorst & Vermaas, 2005; Gero, 2004) in order to improve its description capabilities.

Engineers are interested in understand how "*things work*" (Vincent, 2003). Julian Vincent, a Biologist that is working in the field of Bio-Inspired Design all his academic life has provided this statement. In fact, a deeper understanding of the phenomenon can increase the dimension of the solution space.

The research groups that have developed the two main models for Bio-Inspired Design tasks have followed this "philosophy".

The former is the SAPPhIRE model (Chakrabarti et al., 2005) proposed by prof. Chakrabarti's research group at the Centre for Product Design and Manufacturing – Indian Institute of Science.

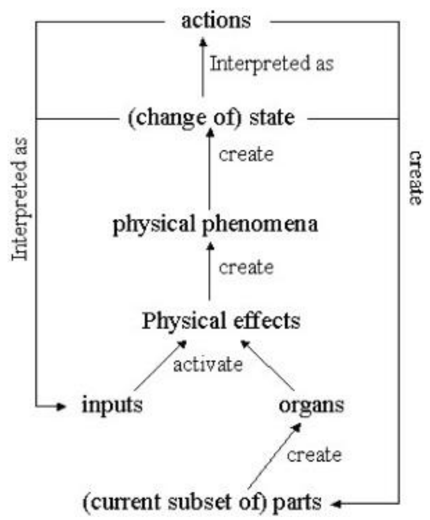
The latter is an approach for modelling called DANE Design by Analogy to Nature Engine (Vattam, Wiltgen, et al., 2010) proposed by prof. Yen's research group at the Centre for Biologically Inspired Design of the Georgia Institute of Technology.

Among the BID models available in literature, DANE and SAPPhIRE certainly share the greatest attention for both the consistency and the regularity of their development over the years. Besides, these models cannot be considered as alternative frameworks, since they are characterized by substantially complementary characteristics (Baldussu, Cascini, Rosa, & Rovida, 2012).

SAPPhIRE: a Causal model

Chakrabarti and his research group (Chakrabarti et al., 2005) developed "a generic model for representing causality of natural and artificial systems" to "structure information in a database of systems from both domains". They developed a causal language (the acronym of which is SAPPhIRE) to describe structural and functional information of natural and technical systems. This language was conceived to put in evidence the sequence of physical phenomena governing the "functioning" of the system. In other words, SAPPhIRE has been designed to put the emphasis on the causal relationships among the phenomena that guarantees the delivery of a system function.

Figure 1.24 SAPPhIRE model (Chakrabarti et al., 2005)



In the SAPPhIRE model (see Figure 1.24), it is assumed that an external input together with a particular "configuration" (called organ) of the system (simply described by the list of its parts) activate a Physical Effect, that results in a Physical Phenomenon capable to change the State of the system. This causally related sequence of elements is suitable to describe any change of state. Normally, it is used to describe the "main" change of state of the considered system (interpreted as the desired Action).

Starting from the first paper published in 2005 (Chakrabarti et al., 2005), Chakrabarti and his research group continuously improved and extended the SAPPhIRE model as documented by several publications: they improved the definitions of the main components of the model, and introduced and continuously enriched the definitions of the secondary elements of the model.

Actually, the definitions of Parts and Action did not undergo a significant evolution. Besides, in the definition of State, any reference to time (or instant) disappeared in 2010. This evolution is in accordance with the main scope of the SAPPhIRE model, that is to represent the causal relationships that justify the system functioning. In this perspective, the description of the time dynamics within the system becomes less important.

It can be noticed that the definition of Organ evolved from the "structural context" required for an interaction, toward the "properties and conditions" required for an interaction.

In principle, these two definitions do not seem to conflict to each other, but the first is useful to better understand the latter. The "properties and conditions" of system and surrounding environment are not only specific properties (the temperature of a part, for example), but can refer also to connections between different parts and to the possibility of interaction between them.

These reflections comply with the use of Organ to represent the system structure, as proposed by the authors of the model in (Srinivasan, Chakrabarti, & Lindemann, 2012a). It is also worth noting that the environment is explicitly mentioned, recognizing its fundamental importance in biological phenomena (Rosa et al., 2011; Vattam, Wiltgen, et al., 2010).

Analyzing Input definitions, it can be concluded that an Input is a particular property of the environment that triggers the Physical Effect, thus producing the Physical Phenomenon; as such, the Input should be distinguished from the system properties that enable the Physical Effect and are described by the Organ.

In fact, the Physical Effect is the general principle underlying the Physical Phenomenon. The Effect can be considered as the abstract description of the physical principle (i.e. its theoretical laws and governing equations), while the Phenomenon is the practical embodiment of the Effect, conditioned by the actual properties of the physical system (Organ).

In other words, the peculiar condition and configuration of the system (Organ) grants only the possibility that a Phenomenon occurs according to a specific physical principle (Effect), but not its actual occurrence, that is conditioned to a triggering event (Input).

FBS models in Bio-Inspired Design: DANE

While functional models are mainly focused on device input and output, the FBS models put emphasis on the representation of the internal processes, the consequence of which are device output states (see, for example, (Bhatta & Goel, 1994).

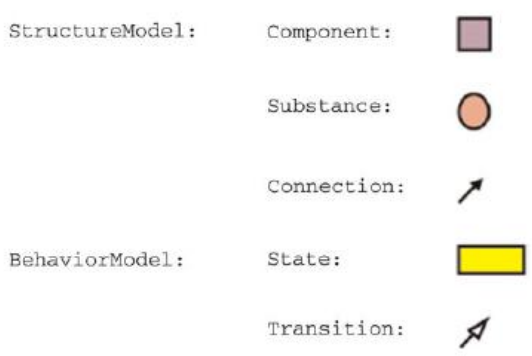
Among the systems explicitly based on the FBS framework, DANE is probably the most acknowledged in the BID community.

The origin of this FBS model (Vattam et al., 2011) lies on the Functional Representation (FR) schema (Chandrasekaran, 1994; Stroble, Stone, & Mcadams, 2009). Even if this model was conceived to represent Structure, Behavior and Function, the causality of relations is not ignored. In the FR schema, "how the device achieves the function is given by a Causal Process Description (CPD)", that, according to Chandrasekaran, "can be thought of as a directed graph whose nodes are predicates about the states of the device, and links indicate causal transitions."

Goel and his research group continuously evolved the FBS model (Goel, Rugaber, & Vattam, 2008) and finally applied it in the Biological Inspired Design field (Vattam, Wiltgen, et al., 2010). The more tangible result is an interactive tool for supporting BID called DANE (Design by Analogy to Nature Engine), that was conceived to provide ''access to a design case library containing Structure-Behavior-Function (FBS) models of biological and engineering systems'' (Vattam, Wiltgen, et al., 2010).

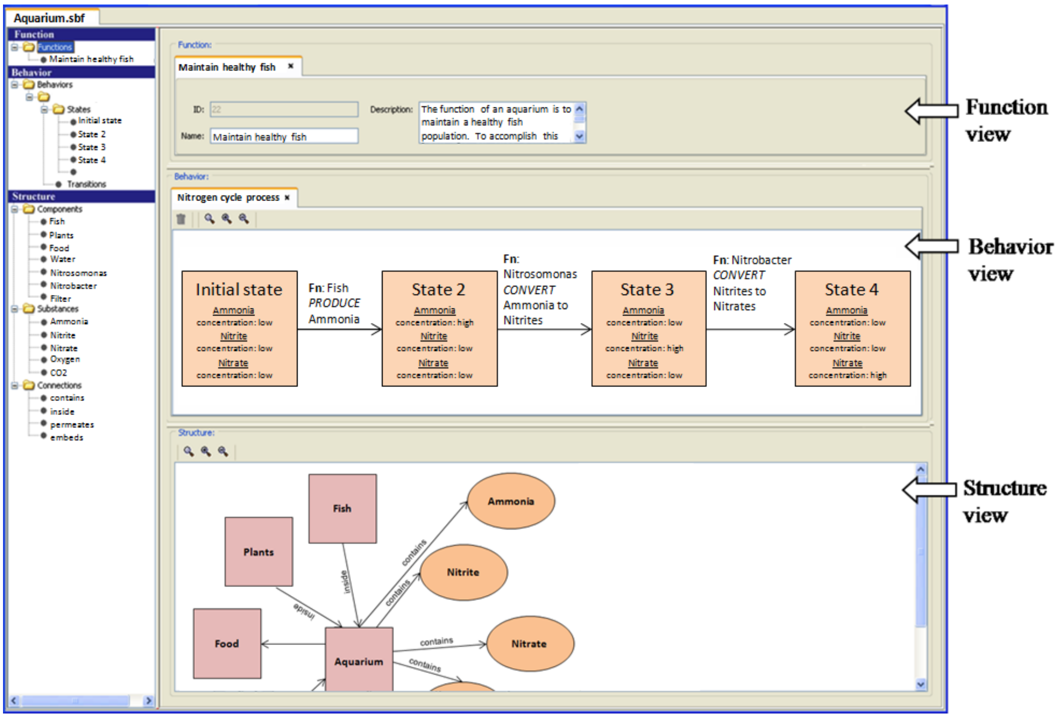
In this model, the function is represented by means of a schema that specifies "initial" and "final" conditions of the system, with the aim of representing what the system actually does. The function is accomplished through a progression of states through which the system evolves, each described by a set of physical variables defining the relevant properties of the system. The behavior consists of this sequence of states, together with the causal explanation of the transition between them (Design & Intelligence Laboratory - Georgia Tech, 2011). Usually, these explanations consist in a physical phenomenon or principle that governs the state transition. Finally, the structure is represented by means of a box diagram. Figure 1.25 shows an example.

Figure 1.25 DANE modelling approach – vSBF language (Vattam et al., 2011)



The formal definitions of the main components of their model can be found in a previous paper (Goel et al., 2008). Beside these theoretical definitions, it is also worth considering how they are implemented in the DANE software, in order to better clarify their underlying significance.

Figure 1.26 A snapshot of FBS interface (Vattam et al., 2011)



The Function is defined by means of four (three main mandatory and one optional) elements (Design & Intelligence Laboratory - Georgia Tech, 2011):

- Verb associated with the function,
- Subject of the function (i.e. the function carrier);
- Object(s) of the function (the recipients of the function).
- Preposition(s) (describing the environment or particular conditions/requirements), and Adverb(s) (such as “quickly”, “efficiently”, or “stealthily”) can be added to describe the function in more detail.

The specification of these elements shows that function definition in DANE is close to the classical <Verb> <Noun> schema (Pahl et al., 2007), and to some related evolutions (Rosa et al., 2011). Nevertheless, this way of storing function definition does not seem in contrast with the theoretical definition. It allows describing what the system “makes”, starting from a “given” initial condition (pre-condition).

According to its theoretical definition, the behavior is represented by means of a state transition diagram. This representation provides a causal explanation of system “functioning”, describing how it evolves to reach its goal (accomplish function). Each state is described by a set of physical properties of the parts (i.e. a set of (object: property: value) triplets, so that it is possible to link each property to the relevant part), while the causal explanations of each transition can be one of the following: external stimulus, structural connection, principle, function and transition.

The Structure is represented by means of a diagram showing "the set of objects related to the system and their relationships, as of the initial state of the system. Objects are represented as boxes, relationships between objects as arrows with annotations representing the kind of connection relationship" (Design & Intelligence Laboratory - Georgia Tech, 2011). The objects and the annotations do not follow any prescription and can be arbitrarily defined by the user.

1.4.3 - The methods used in Bio-Inspired Design

After a first stage of evolution of Bio-Inspired Design where the goal has been the development of a set of ad *hoc examples* of BIPs, the scientific community moves its interests in the definition of methods that allows applying the BID systematically.

Several methods, for both the Problem-Driven and the Solution-Driven approach, have been proposed in literature (Helms et al., 2009; Lenau, 2009; Lindemann & Gramann, 2004; Schilling et al., 2005). For the purpose of the research, we are interested only in the methods suitable for the Problem-Driven approach that allow starting from the technical problem and obtaining a Nature-Based Conceptual Solution.

1.4.3.1 **Bionic procedural model** (Lindemann & Gramann, 2004)

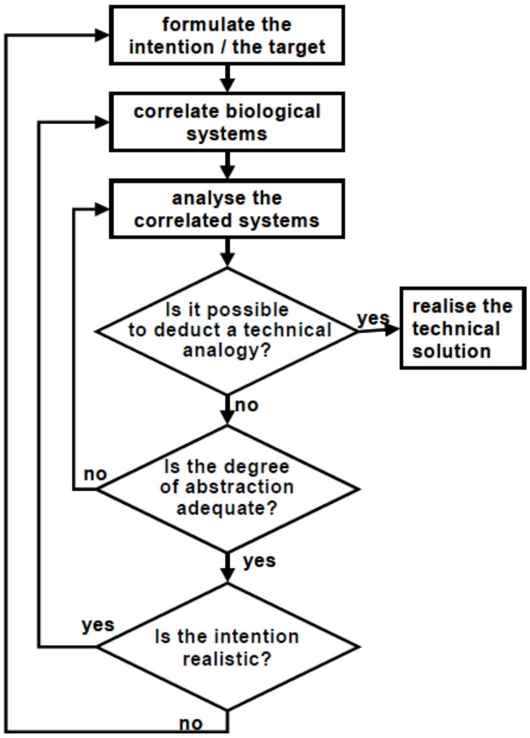
According to the authors, the euphoria about Bio-Inspired Design was impressive but during the daily business of engineering designers, BID has absolutely no importance. The research conducted by (Lindemann & Gramann, 2004) has been aimed at using insights into Nature i.e. Biological principles when designing technical systems in the field of mechanical engineering. In order to avoid that the matters misused as a marketing strategy by using some biological comparison constructed after completion of the product development, they want to realize a procedure that fits to the engineer's way of solving problems.

Five steps constitute the procedural model:

I. Formulate the intention/target
II. Correlate biological systems
III. Analyze the correlated systems
IV. Deduce a technical analogy
V. Realize the technical solution

It is important to note that *step IV* foresees the first of the three control questions of the procedural model. In fact in this step is verified the possibility to deduct a technical analogy. The procedural model poses other two control questions. These two questions are related to the level of abstraction and the search target.

Figure 1.27 The Bionics procedural model in the Product Development (Lindemann & Gramann, 2004)



The focus of the research is about the possibility to create a biological association to the technical problem. In fact, the authors provide a checklist to verify the link between the individuated NSoI and the correspondent Nature's solution and the design problem to solve.

The checklist correlates the main function of the system, declined in various forms using a functional verb correlated to an object/field/parameter and the associated biological term.

Table 1.4 Excerpt of the transfer checklist between technical functions and terms in Biology (Lindemann & Gramann, 2004)

function I	function II	object / field / parameter	Associations
change of the state of aggregation	sublimate	solid	- (?) -
	vaporise	liquid	sweating (passive), spongy parenchym of a leaf (passive), bombardier beetle (brachynus) (active)
	condense	gas	nose passages, plants and animals living in desert, leaf
	melt	solid	spermaceti of sperm whales (physeter macrocephalus)
	dry / dehumidify	solid	splaying plumage (e.g. phalacrocorax carbo), dehydration in the intestine, shaking the fur, hydrophobic treatment by lipids, osmotic potential, seed of plants

The checklist has the aim to build a bridge between functions in engineering and biological areas as a kind of association to finally finding adequate biological principles.

The procedural model has been obtained by a set of two industrial problems and tested developing a solution using Natural Sources of Inspiration.

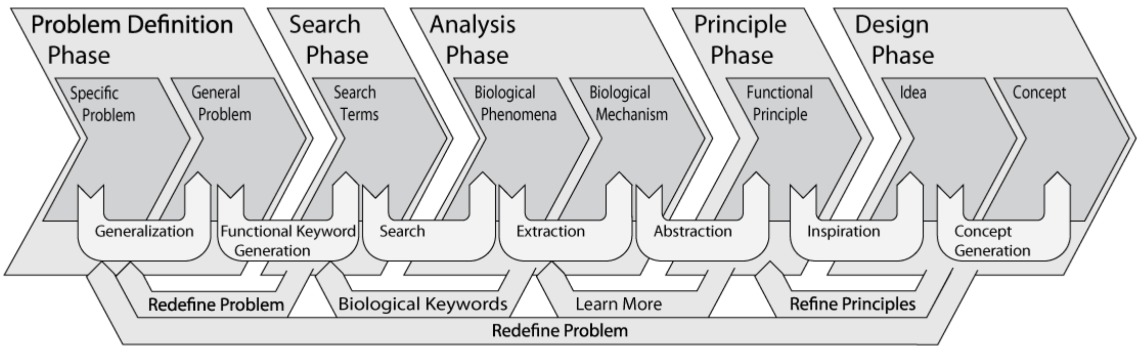
1.4.3.2 Biomimetic as a design methodology (Lenau, 2009)

Lenau proposed a methodology composed by five steps composed by methods in three of them and four feedbacks within the steps.

I. Problem definition phase
   a. Generalization
   b. Functional keyword generation
II. Search phase
III. Analysis phase
   a. Extraction
   b. Abstraction
IV. Principle phase
V. Design phase
   a. Inspiration
   b. Concept generation

The generalization, as a part of the definition phase of the problem, allows passing from the specific problem to the general problem. Generating functional keywords is possible to search for biological phenomena. The analysis phase allows extracting the biological mechanism from the biological phenomena individuated during the keyword search. Then the abstraction allows passing to the principal phase where the functional principle is used as inspiration to generate an idea. The idea in the design phase allows the generation of the concept.

Figure 1.28 The biomimetic as a Design methodology (Lenau, 2013)



The feedbacks foresee in the methodology are:

i. Refine principles
ii. Learn more
iii. Biological keywords *(insertion – refinement)*
iv. Redefine the problem

Refining the problem is possible to go back to the principal phase in the case of difficulties in the implementation of the idea in a feasible concept. Sometimes it is necessary learn more about the biological phenomenon in order to better describe the biological mechanism. Is it also foreseeing the possibility to “rework” the biological keywords in order to improve the search phase. However, if the search phase does not give satisfying results it is possible redefine the problem in order to head in a new direction the search. Even though the process has reached the last step, the design phase, it is provided the possibility to perform a complete feedback in order to redefine the problem coming back to the problem definition phase.

The methodology has been used in an experiment involving 12 design-engineering students for seven selected problem areas. In fact, the research conducted by (Lenau, 2009) was aimed at demonstrating the possibility to use commonly available literature i.e. university library books and journals and internet resources i.e. search engines.

1.4.3.3 Biologically Inspired Design process (Helms et al., 2009)

The goal of the research conducted by (Helms et al., 2009) was about the understanding of the process of biologically inspired Engineering Design in order to provide insight into Biologically Inspired Design as a typology of design activity. In the study have been followed both the Solution-Driven and the Problem-Driven. For the purpose of the comparison with the other BID approaches, hereafter it will be considered only the Problem-Driven approach.

In the study, the authors have individuated a set of six main activities during the Problem-Driven BID:

- **Step 1:** Problem Definition
- **Step 2:** Reframe the Problem
- **Step 3:** Biological Solution Search
- **Step 4:** Definition of the Biological Solution
- **Step 5:** Principle Extraction
- **Step 6:** Principle Application

In step 1, after the definition of the problem, this is described by functions. In order to handle complex problems, these are illustrated by means of several hierarchical levels. Engineers and biologist have a different way of describing phenomena. The second step, i.e. reframe the problem; it is used to translate the technical problem into a biological description. That is necessary to search within the NSoI in the next step.

Then in the third step, i.e. the NSoI search is aimed in finding the one that appear adequate concerning the given problem. The individuated NSoI are structured and their functions are defined in order to improve the understanding of them.

After examining and understanding the NSoI in detail, working principles are selected in the principle extraction phase. The aim of step 6 is to technically describe the chosen overall solution with the technical solutions of its natural working principles in detail.

The process has been obtained by a study of the behavior of designers during the BID projects. The research was a project-based undergraduate class, in which 45 students, 41 of whom were seniors, work in small teams of 4-5 designers on assigned projects. The class was very interdisciplinary, composed of 6 biologists, 25 biomedical engineers, 7 mechanical engineers, 3 industrial engineers, and 4 from other majors.

1.5 - State of the Art: Conclusions

Nature's solutions have been tested by evolutionary needs for 3.8 millions of years, the result are forms, functions, structures, materials and so on extremely efficient and refined. Thanks to this huge Trial & Error lab it is possible to conclude that Nature as a Source of Inspiration could present several advantages in the design field.

Furthermore, it is important to note that, if none competitors have already used a specific Nature's solution in one of their products and the derived BIP has not been already patented in order to gain a commercial advantage; it is possible to use the Nature's solutions freely because:

Nature's solutions are not patented.

Among the possible approaches that use Natural knowledge as a source of inspiration for design purposes, in the present research has been decided to follow the Bio-Inspired Design approach defined by (Vattam, Helms, et al., 2010):

> *"[…] an approach to design that espouses the adaptation of a function and mechanism in biological sciences to solve Engineering Design problems […]"*

The above-mentioned definition is the one that clearly describes the type of the natural knowledge that is used to improve the performance of technical products and the field of application i.e. the Design tasks.

Focusing the attention on the Product Design and Development Processes two conclusions about the use of Nature as a source of inspiration can be drawn.

First of all, it is important to identify if in the PDP has been foreseen the use of Nature as a source of inspiration in a structured manner within the methodology. The German school of Engineering Design has explicitly considered, since the sixties of the last century the possibility to search for working principles into the Natural domain in order to solve technical problems. In any case, the authors have given no indication about the use of this knowledge. On the other hand, the approach proposed by (Ulrich &

Eppinger, 2012) foresees the possibility to perform Eco-Design but not of using Nature's solution to improve the design of technical products.

Secondly, comparing the two approaches in terms of the product development process features, it emerges that they share the same design phases even it is possible distinguishing several differences for the specific tasks. For example, they share the second step, i.e. the Conceptual Design phase. In the (Pahl et al., 2007) approach the phase is extremely structured and the final concept is obtained by the selection among a set of working principles. On the other hand, in the (Ulrich & Eppinger, 2012) approach it is provided a five-step method to develop a set of conceptual solutions to be compared in order to select the most promising one.

Moving to the analysis on the use of Nature knowledge in research activities it is possible to conclude that both disciplines Biology and Physical Sciences grow. In the technical field, research is mostly aimed at the realization of a technical version of the entire natural system. With this aim, researchers can provide to Space and Defense Agencies the most advanced systems to carry out difficult tasks in hostile environments. On the other hand, in Biology with the results of the engineering analysis of the Natural systems the understanding of the natural phenomena increases.

Instead, the BID consultants and the companies have a more practical vision about the use of Nature as a source of inspiration. In fact, they are interested in learning more about natural phenomena and in the specific about Nature's solutions in order to improve the design of products. In particular, in industry can be identified two predominant interests in the use of Natural knowledge for design activities. Roughly speaking in Industrial Design the interest is more on the use of shapes and the animals' posture in order to improve the aesthetic; on the other hand, in Engineering Design the focus is on the use of functions and mechanisms in order to improve the performance of the technical products.

In the recent years, some companies have misused Nature in order to give a "natural soul" to their products. The NSoI has been used only as a marketing tool and not as a new way of solving technical problems. Big companies such as Airbus, Dunlop etc. that have enough resources to invest in a new way of designing their products are showing interest in using Natural knowledge in terms of Nature's solutions into their product even if there is not a direct correlation between the overall shape of the product and the NSoI.

Nowadays the possibility to carry on a BID project is limited only for big companies, which have budget that allow the consultancy with teams of experts both from biology and from the technical world. In fact, considering the potentiality in using Nature's solutions for the development of new products this limitation is not acceptable.

Focusing the attention to the above-mentioned Product Development Processes, the Problem-Driven approach seems to be the most appropriate one in order to carry on BID projects. The PB-Driven approach needs to find a correlation between the technical problem under development and the Nature's solution that has been selected.

The information available for the BID approach can be found in two different “tanks”, i.e. specialized books and scientific journals or databases of natural phenomena. The formers present a limitative solutions space due to the fact that are presented concepts already developed. In any case are a fundamental source of knowledge and information to increase the knowledge about a specific Nature’s solution. The latter at the moment seems to be the most promising approach to retrieve Nature’s solutions for Bio-Inspired Design purposes.

For example, the database developed by the BIOMIMICRY 3.8 INSTITUTE presents several advantages. The natural phenomena are classified using a Natural functional taxonomy i.e. the Biomimicry Taxonomy that allows correlating easily the technical problems with the natural strategies considered as Nature’s solutions. Mainly Biologists create the entries of the database and each of them is correlated by information about biological scientific publications relative to the natural phenomenon and the names of expert scientists in the matter. Moreover, thanks to the use of the database by the consultancy of the Biomimicry institute i.e. the BIOMIMICRY GUILD, the number of entries in AskNature.org grows daily.

The use of functional and causal models allows creating a structured description of a system. In particular, these models allow answering the question *how does it works?* In the BID field designers use modelling approaches such as SAPPhIRE and DANE to describe the NSoI. This structured description of the knowledge about the natural phenomenon makes usable the biological knowledge to the designers and allows easily transferring it to the technical domain.

These two models are the only ones that have received regular improvement and extension by the two authors. They are able to describe both the NSoI and the technical product but even if they share the same aim, cannot be considered as alternative frameworks. In fact, they present a complementary view of the natural system and this fact may increase the solutions’ space available for the design phase.

Several methodologies have been developed in order to systematically structure the BID process. All the methodologies share the same steps but none of them gives complete indications about the methods and the tools to use in order to carry on all the steps.

(Lindemann & Gramann, 2004) provide a checklist in order to compare the technical functions and the biological terms. (Lenau, 2009) proposes to use books and internet search engines in order to individuate the most appropriate NSoI but leaves completely to the designer’s ability the application of the following steps. These choices limit the repeatability of the method and create the need of having several loops to go back to the previous step if the designer is not able to go ahead with the application of the methodology. These two frameworks show an iterative structure that is not acceptable in nowadays industry’s approach characterized by the concurrent engineering.

On the other hand the process proposed by (Helms et al., 2009), shares with the other approaches the number of the steps and the goals of each one, but is characterized by a linear structure. Moreover, with respect to the other approaches the application of this methodology has a statistical validity thanks to the fact that the study has been performed on a statistically significant pool of designers.

1.6 - Hypothesis and Research Questions

In order to start working on Bio-Inspired Design a main hypothesis has to be accepted:

Nature's solutions can be a source of innovation in the product development process.

The aim of this research is the integration of the correct BID tools into a Problem-Solving methodology usable by designers without Biological knowledge that allows a systematic development of BIPs.

In order to achieve this result it is necessary to answer to the following research questions:

i. *How a designer can be guided to use nature as a source of inspiration in order to solve technical problems?*
ii. *What is the industrial applicability of a method of Problem-Solving based on the use of the tools currently developed by the scientific community for the BID?*
iii. *How these tools can be integrated into the Product Development Process?*

Answering the first research question will allow individuating the correct tools and methods to guide the designer in the description of the problem, the translation of it in biological terms, the individuation of the NSoI, and the correct extraction of the biological knowledge useful for the design phase.

The test of the methodology on industrial problems will allow to individuate the applicability of it in terms of type of solvable problem, features of the products that can be developed and designer's characteristics, i.e. design experience, biological knowledge and level of necessary instructions about the methodology.

Finally it will be individuated the possibility to insert the BID Problem-Solving methodology into a standard Product Development Process.

2 - Methodology proposal

This section presents the original contribution of the research work: a Problem-Solving methodology for Bio-Inspired Design. The methodology is based on the process proposed by (Helms et al., 2009) and is developed following the Problem-Driven approach. It is organized in six steps and is a combination of tools and methods developed ad hoc that guide the designers in order to carry out properly each step.

The proposed tools have been selected from the scientific literature. Where necessary they have been improved otherwise they have been specifically developed by the author. Moreover, the methods have been deduced by two main research activities the analysis of a set of BIP and an on-line survey to Biologists.

Section 2 is composed by 7 sub-chapters and can be divided in three main sections. The first one presents the overall structure of the Problem-Solving methodology. The second part presents the specifications about the steps of the methodology that foresee methods in order to carry out properly the step. Each of these chapters is structured in the same way, i.e. the method, the tools, and the output of the step. Finally in the last section is presented an integrated models i.e. the SAPPhIRE-DANE model that is aimed at enhancing the modelling capabilities for the step 4 i.e. the definition of the Nature’s solution.

2.1 - Overall goal of the activity

The importance of the use of Nature as a source of inspiration along all the history of Design and the growing interest in using different design strategies has been widely discussed in section 1. From the analysis of the state of the art emerges that it is necessary reduce the gap between BID research and industry.

Usually only big companies can afford this type of Design. The main reason is the need of using enormous amounts of money in consulting with Biologists or specialized teams of Bio-Inspired Designers. Moreover, to properly develop a BID project is usually necessary a certain level of Biological Knowledge inside the design team. Unfortunately, the Biological knowledge is not present in companies of design and manufacturing for at least two reasons. The first is the absence of need to have biological knowledge in everyday design task and second because the Biological knowledge is incredibly large and diverse.

These limitations aim the research presented in this thesis in developing a Problem-Solving methodology that allows guiding the designers without Biological knowledge on performing properly Bio-Inspired Design. The methodology will be based on freely available resources. This feature may allow SMEs to adopt it into their daily Design activities without extra costs at least in the conceptual design phase. Furthermore, the methodology will be easily inserted in the most diffused approaches of Product Design and Development without requiring modification.

The methodology has to be usable also from young designers with a limited experience i.e. 2nd or 3rd design experience and a basic knowledge on the methodology.

Finally, the methodology can guide the designer in the development of products that are characterized by a certain level of complexity. According to the classification proposed by (Hubka & Eder, 1988) the level of complexity that we are interested varies from level 1 (i.e. Part, Component - Elementary system produced without assembly operations) to level 3 (i.e. Machine, Apparatus, Device - System that consists of sub-assemblies and parts that perform a closed function).

2.2 - The Problem-Solving Methodology framework

From the comparison of the methodologies proposed for BID tasks in the area of the Problem-Driven approach, it is possible to say that all of them share the same steps. Due to the need to define specific activities and methods to carry out each step of the methodology it has been decided to adopt the process proposed by (Helms et al., 2009):

Step 1: Problem Definition

Step description: *After defining the problem, it is described by functions. In order to handle complex problems these are illustrated on different hierarchical levels.*

Step 2: Reframe the Problem

Step description: *Engineers and biologist have a different way of describing phenomena. This step is used to translate the technical into a biological description of the problem. That is necessary to search within the NSoI in the next step.*

Step 3: Biological Solution Search

Step description: *In this step NSoI, which appear adequate concerning the given problem, are searched.*

Step 4: Definition of the Biological Solution

Step description: *The discovered NSoI are structured and their functions are defined in order to improve the understanding of them.*

Step 5: Principle Extraction

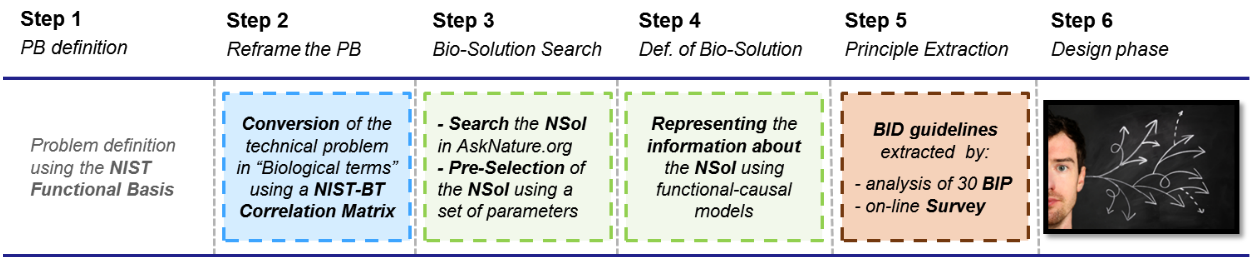
Step description: *After examining and understanding the NSoI in detail, working principles are selected.*

Step 6: Principle Application

Step description: *In step 2, the technical problem has been translated into biological terms. Later in step 5 the natural working principles were extracted from the NSol translated back into technical sub-solutions. In order to fulfil the technical requirements it is possible to combine single sub-solutions from more than one NSol to an overall solution. The aim of step 6 is to technically describe the chosen overall solution with the technical solutions of its natural working principles in detail that represent the final Bio-Inspired Conceptual Solution.*

Figure 2.1 shows an overview of the methodology with all the adopted tools in order to carry on each step, starting from the technical problem in order to develop a Bio-Inspired conceptual solution.

Figure 2.1 The Problem-Solving methodology for BID and the adopted tools



2.2.1 - Step 1: Problem Definition

In the scientific BID literature has been presented at least two attempts of creating taxonomy of functions in order to standardize the description of technical systems. These two approaches developed simultaneously and independently by two different scientists have been reconciled in a project proposed by the NIST – National Institute for Standard and Technologies. The Functional Basis for engineering design proposed by (Hirtz, Stone, Mcadams, Szykman, & Wood, 2002a) is a formal function representation to support functional modelling, and a standardized set of function-related terminology. This approach leads to repeatable and meaningful results from such a representation.

In order to make repeatable the description of the problem it is proposed to use the NIST Functional Basis (Hirtz et al., 2002a) as a tool for the Problem Definition.

Hypothesis:

Among all the kinds of technical problems that can be encountered, we are focusing our attention on those related to a search of different ways to deliver a given function.

Problem Description Type:

The technical problems are thus described in the form: how to... ?

2.2.2 - Step 2: Reframe the Problem

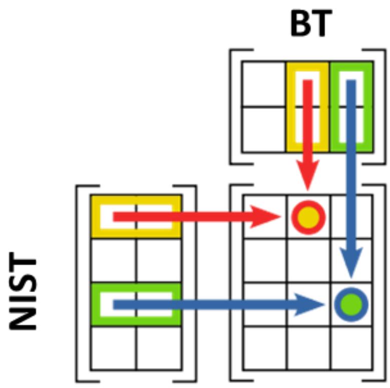
The analysis of the BID literature shows several examples that are aimed at finding a bridge terminology or in the developing of a "dictionary" in order to allow the communication between Biology and Physical Sciences. This is one of the biggest limitations in the application of the BID in fact it is necessary a certain level of Biological knowledge in order to properly individuate the NSoI and understand its biological description.

This step is fundamental for the correct advance of the approach. Indeed here, it is possible making sure that it is not necessary any Biological knowledge for the search of the correct NSoI.

The idea is that developing a tool that allows the designer systematically correlating the functional description of the problem made by using the NIST-FB and the taxonomy of Natural functions i.e. the Biomimicry Taxonomy proposed by the Biomimicry Institute.

An important aspect has to be considered: Designers have developed the NIST-FB and a team of Biologists has developed the BT Taxonomy. This independent development allows separating the knowledge necessary for a correct problem description and an adequate natural phenomena classification.

Figure 2.2 A schematic representation of the Correlation Matrix between the NIST-FB and the BT



A study to understand which functional description was the most appropriated for BID tasks has been conducted in (Baldussu & Cascini, 2011) and allowed the development of the correlation matrix between the two taxonomies:

Technical Taxonomy: NIST Functional Basis – NIST-FB (Appendix B)

Natural Taxonomy: Biomimicry Taxonomy – BT (Appendix C)

Figure 2.2 shows the main idea behind the correlation matrix (Appendix D). In fact, the output of step 1 is a description of the given technical problem in functional terms using the NIST-FB. This description is the input for the use of the correlation matrix that allows translating functions described with a technical terminology into a biological taxonomy of functions.

The final output of the matrix is the class of natural functions that correspond to the technical problem described in functional terms.

2.2.3 - Step 3: Natural Source of Inspiration Search

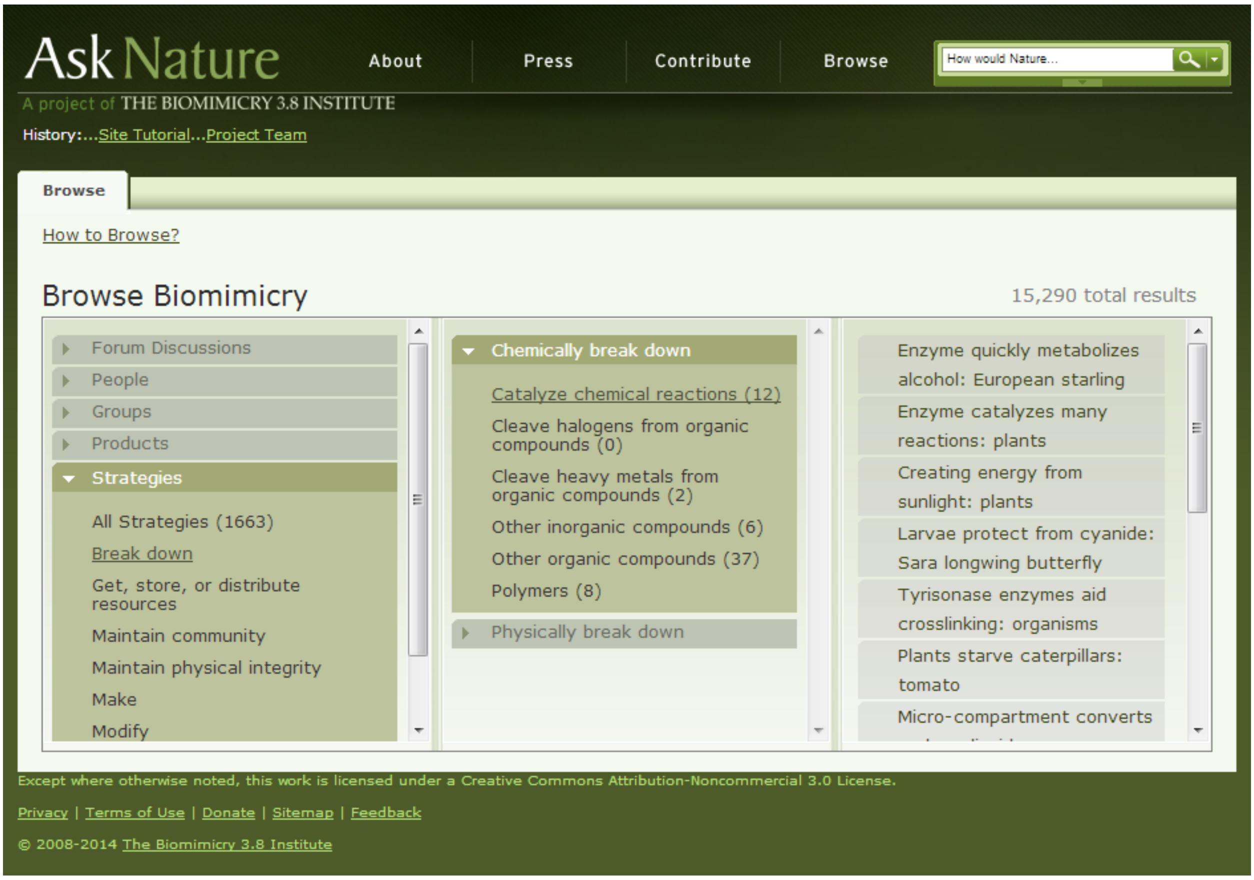
The collection of information about Natural phenomena is an extremely time consuming activity. This task cannot be demanded to SMEs that are interested in having a "first look into Nature" in order to use Nature's best ideas in developing new Bio-Inspired Concepts.

Consultancies specialized in the BID field perform this activity of collecting and storing NSoI for their business. Luckily, one of this consultancies the BIOMIMICRY 3.8 GUILD allows the free use of their database of natural phenomena i.e. AskNature.org

The process of individuation, verification, and storage is supervised and verified by a team of Biologists that have strong competences in BID. This allows designers accessing to a collection of natural phenomena properly classified by experts using a natural functions taxonomy.

The tool proposed for the search step is the AskNature.org database of Natural Strategies.

Figure 2.3 Screenshot of the AskNature DB browsed by categories of natural functions



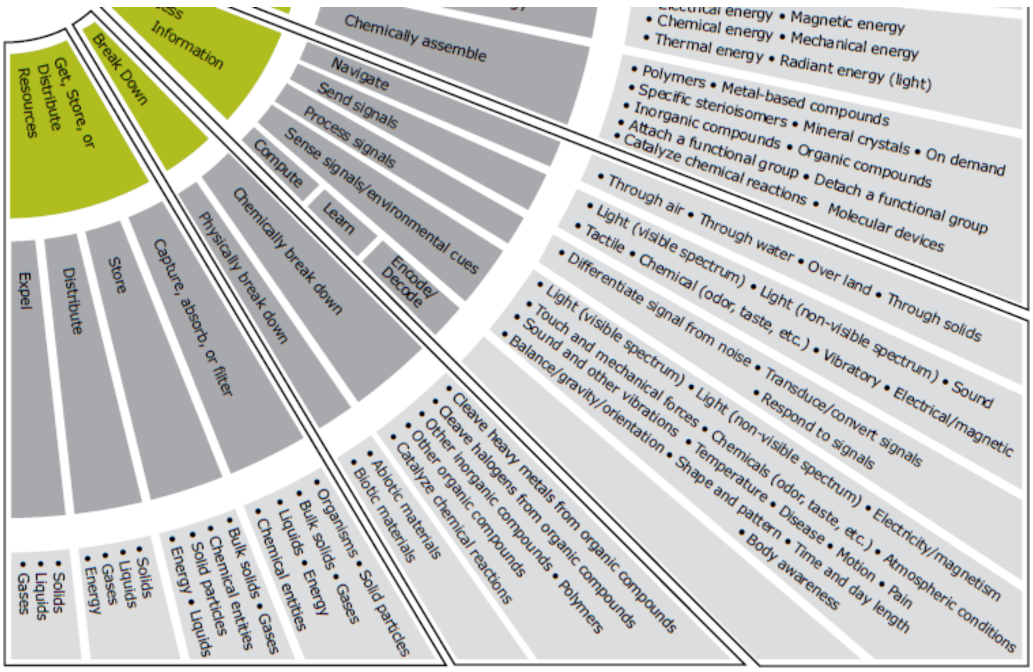
Thanks to the use of the Correlation Matrix presented in step 2 and its output, it is possible to browse the database in a not standard way. In fact, the database has been developed to perform mainly a keyword search. This research strategy requires a certain level of Biological Knowledge to individuate the correct keyword to perform the query. The use of the correlation matrix, allows individuating the correct classes of natural function correspondent to the functional problem under analysis in order to browse the database by functional categories.

Figure 2.3 shows an example of browse of the database by functional categories. In the specific in the browse tab it has been selected the group *Break Down*, this strategy is composed by two sub-groups i.e. *Chemically break down* and *Physically break down*. Then selecting the sub-group *Chemically break down* in the second tab it opens the list of *Natural functions*:

- Cleave heavy metals from organic compounds
- Cleave halogens from organic compounds
- Other inorganic compounds
- Other organic compounds
- Catalyse chemical reactions
- Polymers

as shown in Figure 2.4 and presented in Appendix C.

Figure 2.4 Excerpt of the Biomimicry Taxonomy – BT
(http://www.biomimicryinstitute.org/images//biomimicry_taxonomy.pdf)



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Then for each natural functional class, in the third tab it is opened the list of Natural phenomena i.e. the NSoI that are described from the biological point of view with pictures and text. This NSoI will be used in the following step in order to represent the Natural phenomena by means of functional and causal models and then extract the information for the final step i.e. the Design phase.

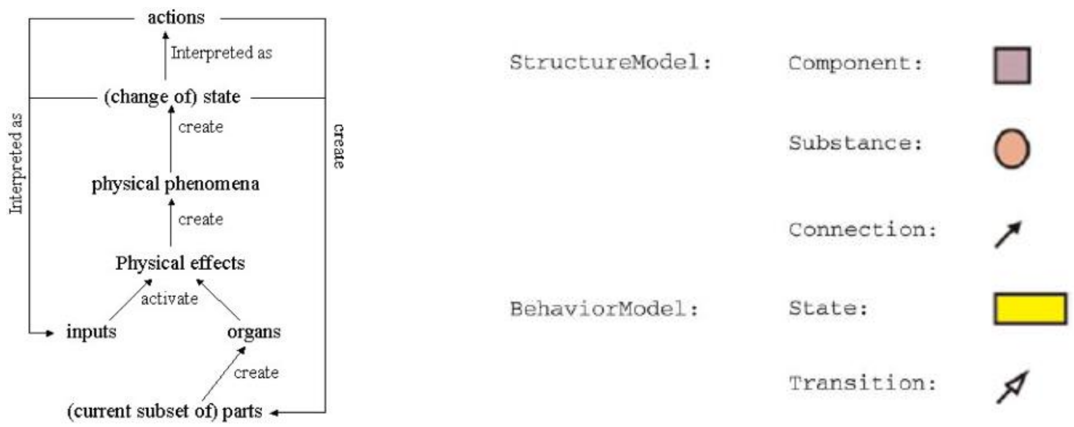
The output of step 3 will be a list of NSoI to be represented by means of functional and causal models in order to obtain a structured description of the natural phenomenon useful for the design tasks.

2.2.4 - Step 4: Definition of Nature's Solution

After the selection of the most promising NSoI, it is proposed using functional and/or causal models to describe the NSoI. From the literature emerges that the two frameworks to perform this task are the SAPPhIRE and the DANE modelling approaches.

While SAPPhIRE is primarily made to characterize the overall system on a high abstraction level at one phase and its connection to the environment, DANE describes detailed the internal structure of the system and its functions in consecutive phases. Thus, SAPPhIRE is more suitable to specify the causal connections inside a natural system whereas DANE enables the representation of different chronological changes of state.

Figure 2.5 SAPPhIRE model by (Chakrabarti et al., 2005) **– DANE modelling approach by** (Vattam et al., 2011)



Depending on the natural knowledge necessary for the problem or the internal functional modelling knowledge of the company, it is possible to choosing to use one model or the other one, either both models or a new model that is the combination of these two models and will be presented in the Section 2.7 -

2.2.5 - Step 5: Principle Extraction

After the description of the NSoI in a structured way it is necessary understand where to start with the extraction of the Natural knowledge useful for the design task. Unfortunately, in literature there are no indications about this aspect of the BID. With the aim of guiding the designer in the development of a BIP using correctly the natural knowledge already individuated in the previous steps it have been provided a set of guidelines.

The tool proposed for this step is a set of guidelines that allows the designer choosing:

i. *The most appropriated part of the model to start with the knowledge extraction*
ii. *Which information has to be extracted in combination with the others*
iii. *Which type of design output will be obtained if it is used one type of information respect to another one*

The guidelines have been extracted by the analysis of the models of a collection of concepts and products that use Nature as a Source of Inspiration. With this aim, a sample of BIPs have been realized extracting randomly 30 scientific papers, from the BID literature, which deal with the solution of technical problems due to the implementation of natural strategies, functions etc. The second criterion, for the selection of the BIPs, is the level of complexity. According to the classification proposed by (Hubka & Eder, 1988) the selected examples are characterized by a level of complexity that varies from *level 1* (i.e. *Part, Component - Elementary system produced without assembly operations*) to *level 3* (i.e. *Machine, Apparatus, Device - System that consists of sub-assemblies and parts that perform a closed function*). Each of the above-mentioned examples of BIPs is considered as a single case study.

Summing up, each case study that has been selected randomly within the Bio-Inspired Design literature is correlated by a scientific paper that provides:

- Information about the NSoI
- Information about the related Bio-Inspired Product

In order to be able to compare systematically the information content of the CS sample, composed by different kinds of concepts and products, it has been necessary to individuate a tool that allows realizing a standard description of the information. The information in the scientific papers is provided by a *textual description*, one for the Natural Source of Inspiration and a different one that describes the Bio-Inspired Product.

Because of the research field and the aim of the analysis, the most appropriate tools to carry on this task are the causal and functional models. As introduced in section 1.4.2.2 the models that are the heavily used in the BID field of research are the SAPPhIRE and the DANE modelling approaches. These models allow representing both the NSoI and the related BIP. Furthermore, due to the different representation perspective of the models and the research aim of analyzing the different type of information implemented in the BIPs it is useful to use both models.

Thanks to the ability of the models in describing both the NSoI and the BIPs, comparing the two models, it is possible systematically comparing the information implemented in the BIP that have been extracted from the NSoI.

According to (Eder & Hosnedl, 2007): *every technical system carries its internal and its external properties, which exist whether they have been deliberately designed, occur as an unintended* *consequence, or arise "incidentally" from the designed structures.* In order to be able of creating a general framework for modelling every technical system, (Eder & Hosnedl, 2007) have developed a comprehensive list of properties that allows describing the transformation process related to each system.

A cluster of comparison has been created in order to realize an analysis independent by the specific modelling tool used i.e. SAPPhIRE and DANE. The cluster is composed by the following categories:

- *Function*
- *Behavior*
- *Structure*
- *List of properties*

Due to the use of the list of properties, it is possible representing extra information that is not represented by the causal or functional models that have been selected as modelling tool for the BIPs.

For each case study, in order to understand which type of natural knowledge and information has been used in the BIPs, it has been applied the following research methodology:

1. *Representation of the information about the Natural Source of Inspiration (NSoI) by means of both the SAPPhIRE and the DANE modelling approaches*
2. *Representation of the information about the Bio-Inspired Product (BIP) by means of both the SAPPhIRE and the DANE modelling approaches*
3. *Comparison between the model(s) of the NSoI and the model(s) of the BIP for:*
    3.1. *SAPPhIRE model(s)*
    3.2. *DANE model(s)*
4. *Check if all the necessary information, for a comprehensive description, is represented by means of the models*
5. *Cluster of the information represented in the models and the eventual extra information necessary for the description of the case study:*
    5.1. *Function (Action, Input and State)*
    5.2. *Behavior (Effect, Physical phenomenon)*
    5.3. *Structure (Organ and Parts)*
    5.4. *Properties*

Step 1 allows creating a collection of models, about the Natural Sources of Inspiration that have been used as a natural phenomenon in the development of each BIP. Both the SAPPhIRE and the DANE models of the NSoI have been created. Then in the step 2, the same method has been applied with the difference in creating that in this case the models are of the BIPs instead of the NSoI.

Given that, the models have the same structure and the same items for representing the information of both the NSoI and the BIP it has been possible to compare, in step 3, the information content of the models for the Case Study *(i)*. The comparison has been made for both the SAPPhIRE and the DANE models of the Case Study *(i).* Thanks to this analysis, it is possible individuating which Natural information has been implemented in each concept/product.

A further analysis, carried on in the step 4, it has been necessary in order to verify if all the fundamental information, for the description of the case studies, has been described by means of the two models. This allows individuating if the causal and functional models for Bio-Inspired Design applications describe completely the BIPs' features especially about the information relative to the NSoI implemented in the technical solution.

Thanks to the comparison made by (Srinivasan, Chakrabarti, & Lindemann, 2012b), between the SAPPhIRE and the FBS based models such as DANE, it has been create a cluster of comparison. This cluster allows individuating, for each case study, which information has been transferred in term of *Structure*, *Behavior* and *Function*. With this expedient, it is possible making an information comparison independent by the modelling tool used i.e. SAPPhIRE and DANE but related to the three categories well established and accepted in Engineering Design.

Furthermore, the cluster has been improved by adding the property list proposed by (Eder & Hosnedl, 2007) allowing us to answer to the research question: *Which biological information is required for the development of Bio-Inspired Products?*

2.2.6 - Step 6: Design Phase

The information extracted by the designers from the Causal or Functional models, following the guidelines provided in step 5 are now implemented into the design of the Bio-Inspired conceptual solution.

In order to do not limit the creativity of the designer in this step no indication about the tools to use are given. The designer is allowed to work with the tools and or the methods more suitable to his/her characteristics. There are no limitations in the design phase neither in the combination of the information nor in the decision of the complete use of the information extracted by the NSoI.

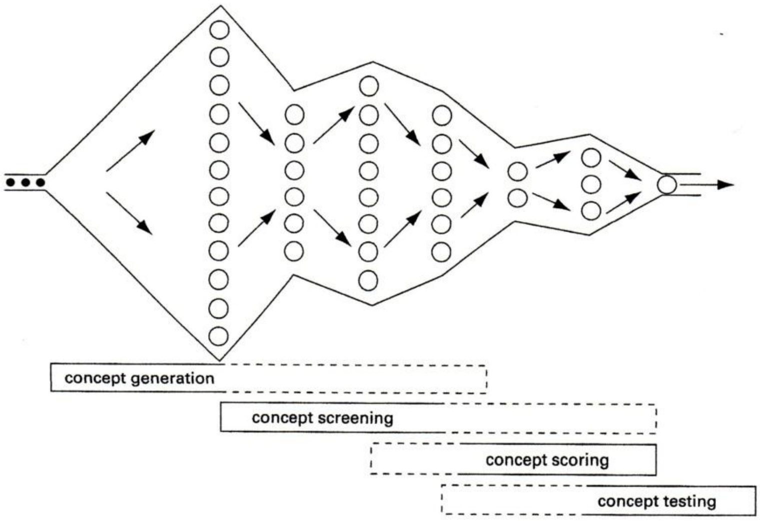
At the end of the process, it is necessary to create a standard description of the conceptual solution with the following information:

- Drawings or sketches
- *Approximate* description (Ulrich & Eppinger, 2012) of the:
    - Technology
    - Working principles
    - Form of the product

Following this indications it is possible to have a standard description of the Bio-Inspired Conceptual Solutions in order to be inserted in the standard conceptual evaluation phase. One suitable approach is the one proposed by (Ulrich & Eppinger, 2012), in fact all the concepts developed for a given technical problem form the conceptual solutions space.

The application of a standard concepts selection method such the one proposed by (Ulrich & Eppinger, 2012) and presented in Figure 2.6 allows to compare the Bio-Inspired Conceptual Solutions with the Concepts obtained by applying standard methods of Problem-Solving.

Figure 2.6 Concept selection methodology (Ulrich & Eppinger, 2012)



2.3 - Specification on Step 2 – Problem Reframe

As briefly introduce in section 2.2.2 - the problem reframe is a fundamental step that creates the bridge between the technical domain and the biological world.

For this step, the designer has to apply a method composed by three tasks and a tool i.e. the correlation matrix, which has been specifically developed by the author to carry on the problem reframe.

2.3.1 - The method

In step 2, it is present the first sub-method in order to correctly translating the problem from technical terms into biological ones. The method is the following:

i. Describe the technical problem in functional terms using the NIST-FB
ii. Use as a input for the NIST-BT correlation matrix the technical problem described in NIST terms
iii. Translate the technical problem in Biological terms finding the correspondent(s) BT class(es)

2.3.2 - The tools

In order to make the Problem-Solving methodology accessible to designers without Biological knowledge it has been necessary to develop a tool that does not require any. In fact, there is no need of biological knowledge in order to individuate the correct class of natural functions, which collect the examples of natural strategies, suitable for the technical problem.

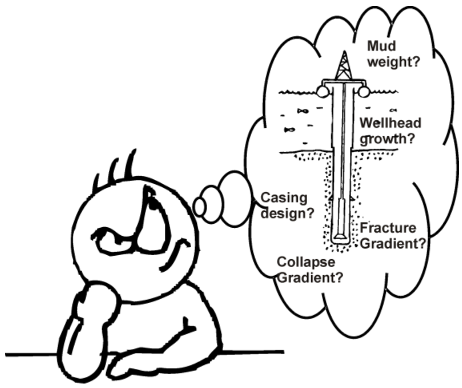
The technical problem will be usually given by a textual description after the process of requirement identification. That allows performing the questionnaire in order to develop a requirement list such in the (Pahl et al., 2007) approach.

In order to explain the process an example is given:

Design Problem:

During the process of designing a new machine that works with a toxic fluid, it is important to prevent any loss of this gas, in order to reduce the risk of ambient contamination

Figure 2.7 A schematic representation of a possible design problem



This description of the problem will be used as a base for the description of the problem in functional terms using the NIST-FB.

2.3.2.1 The NIST functional basis

The NIST-Functional Basis (Appendix B) is taxonomy **of functions** (Hirtz et al., 2002a) expressed by a number of functional verbs applied to EMS i.e. Energy, Material, Signal flows (Pahl et al., 2007).

The formers are **hierarchically subdivided** into:

- 8 classes
- 21 secondary
- 24 tertiary actions on flows

the latter are **classified in three levels** including:

- 6 secondary and 11 tertiary material flows
- 12 secondary and 4 tertiary energy flows
- 2 secondary and 7 tertiary signal flows

Using the NIST-FB is possible to search for the most appropriate combination of functional verbs in order to describe the problem. Considering the textual description of the problem introduced as an example a possible description in NIST functional terms could be:

NIST-FB (Control Magnitude, Stop, Inhibit – Material, Gas)

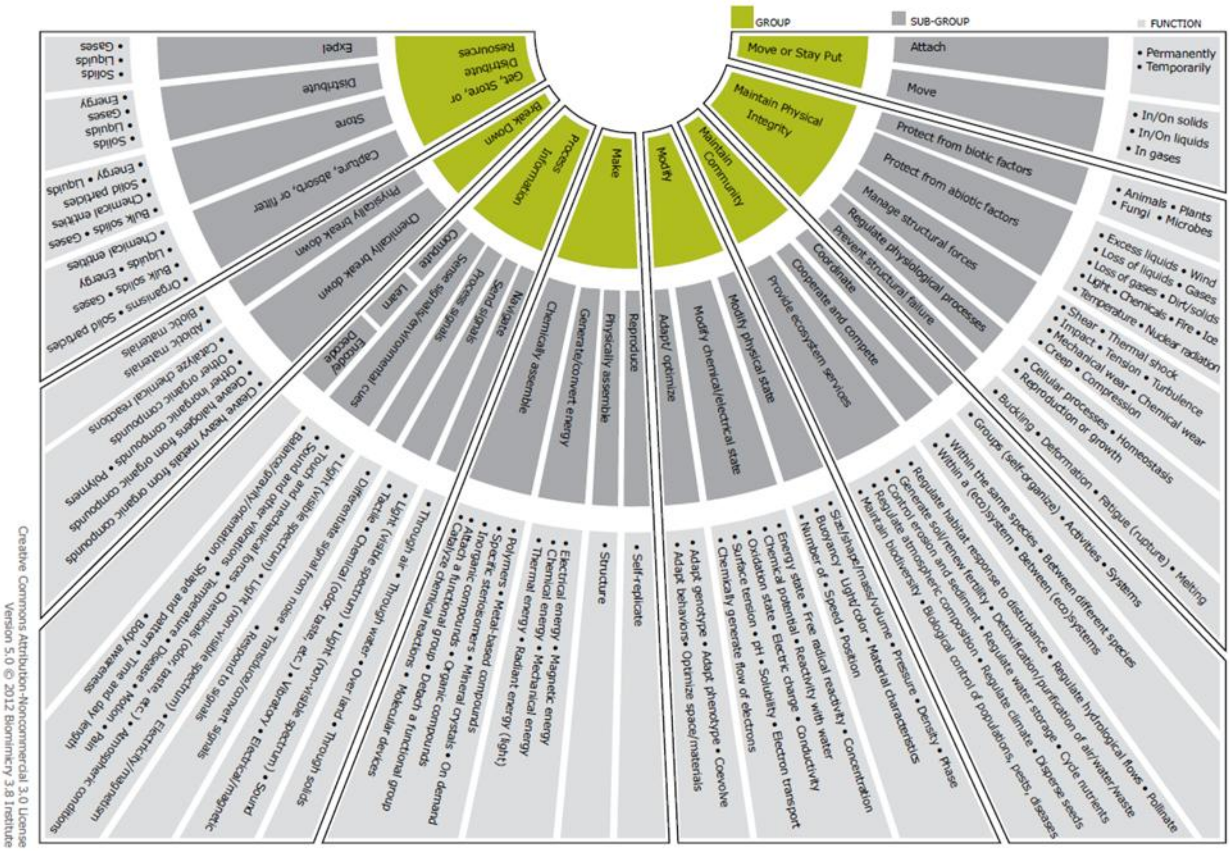
2.3.2.2 The Biomimicry Taxonomy

The BT (Appendix C) is a taxonomy of Natural functions subdivided in three levels:

- Function Groups (8)
- Sub-groups (30)
- Functions (162)

The features of the taxonomy are the followings

Figure 2.8 The Biomimicry Taxonomy – BT accessed on 03/01/2014 at 16.42 (http://www.biomimicryinstitute.org/images//biomimicry_taxonomy.pdf)



The examples of natural phenomena stored in the database are subdivided into the groups as follows:

- ❖ Break down (90)
- ❖ Get, store, or distribute resources (464)
- ❖ Maintain community (286)

- ❖ Maintain physical integrity (1095)
- ❖ Make (204)
- ❖ Modify (398)
- ❖ Move or stay put (311)
- ❖ Process information (357)

2.3.2.3 The Correlation matrix

After the description of the technical problem in functional terms, it is possible to use it as input for the NIST-BT correlation matrix (Appendix D) in order to find the correspondent class of biological functions.

The matrix it has been realized by the comparison of the two taxonomies of functions the NIST Functional Basis and the Biomimicry Taxonomy. Partial results have been presented in (Baldussu & Cascini, 2011) with the specific objective to analyze the taxonomy proposed by the Biomimicry Institute and to map it with respect to the NIST Functional Basis and the OTSM-TRIZ Functional Model.

Figure 2.9 An excerpt of the correlation matrix NIST-FB to BT

NIST Functional Basis	Correspondence	Biomimicry Taxonomy	
• Control Magnitude	• -	• Maintain Physical Integrity	Group
• Stop – Inhibit	• Yes	• Protect from abiotic factors	Sub-Group
• Material, Gas	• Yes	• Gas/Loss of Gasses	Function

The two functional description approaches have been compared with the Biomimicry Taxonomy with the aim of mapping BT groups and functions with the existing engineering descriptions. Both functional modeling systems allow accessing the AskNature.org collection of natural functions, but the OTSM-TRIZ Functional Model revealed to cover a larger portion of the Biomimicry Taxonomy. On the other hand, due to the lack of a reference terminology it potentially suffers for reduced repeatability of the functional triad carrier-action-object. In such cases, a potential negative consequence is a higher number of matches with the BT, with consequent divergence of the problem solving process.

Besides, the specificity of the NIST list of standard flows implies a smaller percentage of complete matches between the action-flow representation and the BT. The analysis of the specific causes of this partial lack of correspondence have revealed that some customization would be necessary. One possibility would be to include in the NIST Functional Basis some specific biological flows in order to reach a better match between these two models.

Due to the heterogeneity of its definition, some modifications are also necessary in the BT, which is characterized by an ambiguous formalism.

Due to the analysis for the final version of the NIST-BT Correlation Matrix, it has been decided to use the NIST-FB as a reference for the description of the problem. An excerpt of the final version is provided in Figure 2.9

Moving from right to left it is possible individuating the correct class of Natural function corresponding to the given technical problem under the solving process.

2.3.3 - The output of Step 2

The application of the correlation matrix allows translating the problem in biological terms. The technical Problem in "BT Terms" will be described as follows:

BT (Maintain physical integrity, Protect form abiotic factors – Gases/ Loss of Gases)

The two classes of Natural functions that have been individuated are:

1. Protect from abiotic factors – Gases
2. Protect from abiotic factors – Loss of gas

The output of the step 2 is the class or the classes of the Biomimicry Taxonomy that corresponds to the class of natural function correlated to the technical problem.

2.4 - Specification on Step 3 – Natural Source of Inspiration Search

This step allows identifying the NSoI that will be the basis for the Bio-Inspired Design conceptual solution development. In order to carry on step 3, the designer has to follow a method composed by four steps and use two tools i.e. the AskNature.org database and the rank-order matrix. The first tool is freely accessible on-line and the second is a standard method to perform a pairwise comparison.

2.4.1 - The method

The output of the previous step is a class of natural functions where each natural phenomenon is applying a specific strategy to perform the above-mentioned "function". Due to the fact, the classes of Natural functions in AskNature.org can be extremely populated it is necessary to provide a method to reduce the number of them to an acceptable amount that can be modelled with the functional or causal models by the designer.

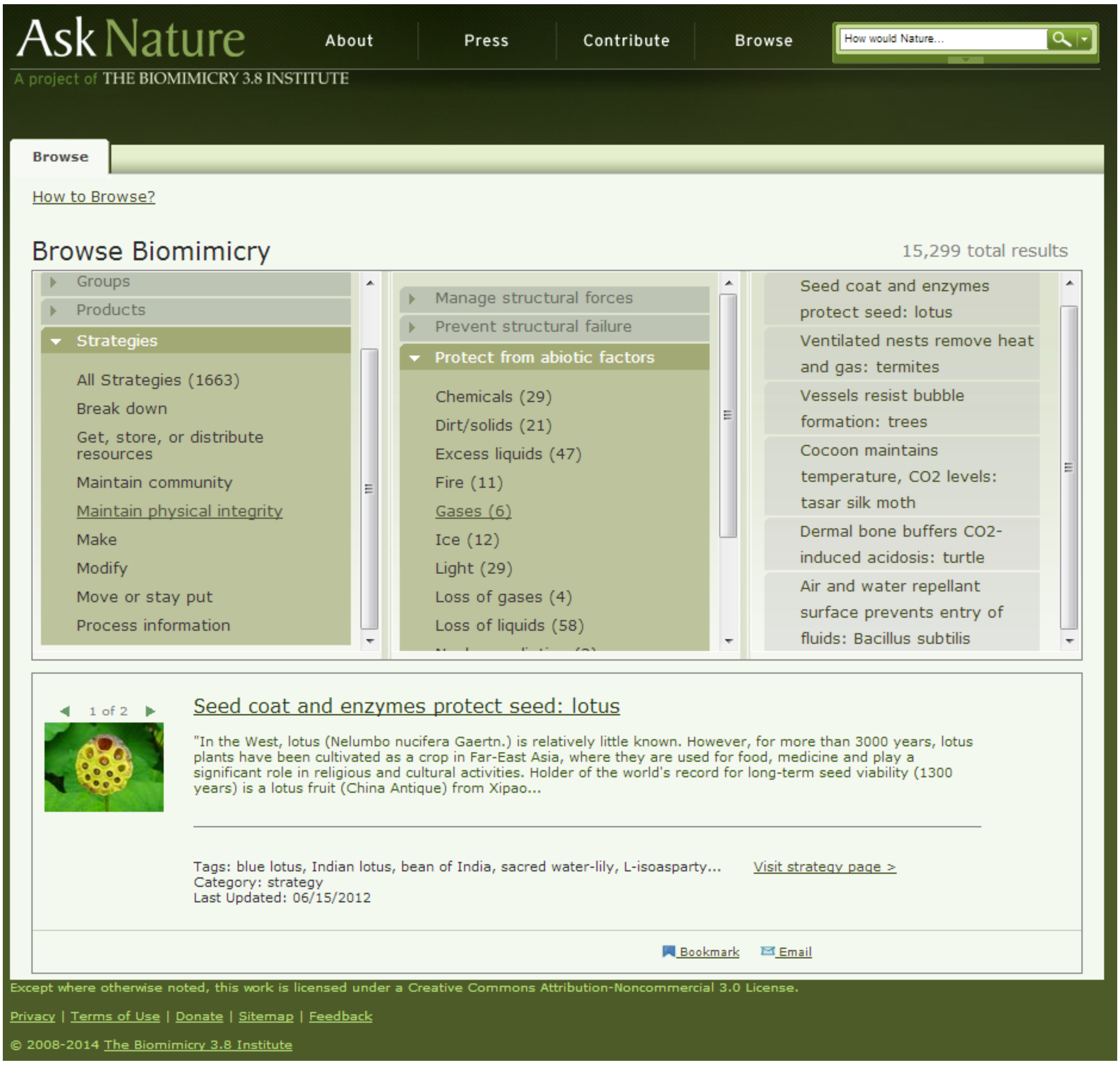
In order to obtain a reduced set of NSoI, usually 3 or 4 example it is necessary to apply the following method:

i. Browse the DB AskNature.org using the class(es) of Natural functions obtained in step 2
ii. Define a set of criterion for the pre-selection of the NSoI
iii. Weight the NSoI by the application of the rank-ordered matrix
iv. Extract from the list of NSoI the most relevant NSoI

2.4.2 - The tools

The core of the BID approach is using Nature's solutions to solve technical problems. In order to accomplish this not standard way of design it is necessary individuating appropriate examples of Natural systems to use a source of inspiration. To carry on the search step two tools are necessary, a collection of NSoI and a tool to reduce them to an acceptable number usable by the designers.

Figure 2.10 A screenshot of the AskNature.org database browsed by classes of natural functions



2.4.2.1 The AskNature.org Database

Using the output of step 2 – the classes of Natural functions i.e. **BT** (Maintain physical integrity, Protect form abiotic factors – Gases/ Loss of Gases) a list of NSoI will be the output of the search.

Considering only the first class i.e. protect from abiotic factors – Gases on the third tab of the database a list with *(n)* NSoI will be provided (see Figure 2.10).

Selecting for example one of the NSoI i.e. *Seed coat and enzymes protect seed: lotus* and clicking on the hyperlink the correspondent strategy page will be automatically opened. For each record present in AskNature it is provided a strategy page, see for example Figure 1.19, which contains a set of useful information such as:

- Picture of the Natural System
- Title of the Natural phenomenon
- Summary
- Excerpt
- About the inspiring organism
- Bio-Inspired products and application ideas
- Experts
- References

Some of the sections are peculiarly important for the BID process and the following steps of the methodology. E.g., the excerpt is a short description of the phenomena extracted by a scientific reference. The information about the inspiring organism reports the scientific name of the organisms that allows the designer to search for further information in the specialized material.

The Bio-Inspired products and application ideas section allows the designer to quickly verify if the idea have been already implemented in other fields of the technics or developed by a competitor.

Then there are some names of experts and finally there are some scientific references about the NSoI.

2.4.2.2 The rank-order matrix

As can be seen simply looking to the second tab of Figure 2.10 the variability of the number of NSoI for each class of functions is extremely high. The following numbers characterize the classes of Natural functions (AskNature.org accessed on 04/01/2014):

- Min. 0
- Max. 130
- Avg. 17

Because it is not possible to make the functional or causal models of all the NSoI obtained during the search phase, it is necessary to identify a method in order to make a preliminary selection of the NSoI in order to reduce the number to a set of 3-4 examples.

Usually, for a given problem, a set of parameters are fundamental for solving it. The parameters can be extracted from the requirement identification process and can be listed in a table (see Table 2.1).

Table 2.1 Example of parameters for the pre-selection of the NSoI

Example of parameters list (in alphabetical order)	
Environmental conditions	A
Existence of a technical application of the Bio-Inspiration	B
Morphological Similarity	C
Phenomenon scale	D
Technological feasibility	E
…	…
Type of Natural System (e.g. plant, animal, cell etc.)	(n)

These parameters, which are determined by the sensibility of the designer, are used as a basis for the pre-selection of the NSoI. Following the standard approach for the pairwise comparison (Cross, 2000):

Each parameter is considered in turn against each of the others

A value 1 or 0 is entered into the relevant matrix cell in the chart, depending on whether the first objective is considered more or less important than the second, and so on. For example, start with parameter A and work along the chart row, asking ***'Is A more important than B?' … 'than C?' … 'than D?' etc.***

- ✓ *If it is considered more important, a 1 is entered in the matrix cell.*
- ✓ *If it considered less important, a 0 is entered.*

Table 2.2 Relevant Matrix for the pairwise comparison of the parameters for the pre-selection of the NSoI (Cross, 2000)

Parameters	**A**	**B**	**C**	**D**	**E**	**Row totals**
A	-	0	0	0	1	***1***
B	1	-	1	1	1	***4***
C	1	0	-	1	1	***3***
D	1	0	0	-	1	***2***
E	0	0	0	0	-	***0***

Thanks to the pairwise comparison, it is possible to rank the parameters in order of importance. In order to perform the pre-selection of the NSoI it is necessary to extract the name, the one line description, and the summary of the entire list of NSoI obtained during the search phase. Inserting all the information in a matrix such the one presented in Table 2.3 it is possible to quickly compare the information about the NSoI and the set of parameters. In the example presented in Table 2.3 it has been choose to use a set of four parameters the first four *A*, *B*, *C* and *D*.

Table 2.3 The pre-selection of the NSoI matrix

	Level of Appropriateness								
	1 – Absolutely inappropriate 2 – Inappropriate 3 – Slightly inappropriate	4 – Neutral	5 – Slightly appropriate 6 – Appropriate 7 – Absolutely appropriate						
				1	1	1	1	6	Min
	Total Number of NSoI	21	14/05/2013	7	7	7	7	42	Max
	Natural Source of Inspiration for BT Class: **Make/Physically assemble/Structure**	One line description	Summary	a	b	c	d	Row Totals	
1	Structure and shape provide flexibility: vines	Architecture of vines increases flexibility via soft tissue components and ribbon-like shape.	There is another way in which the stem anatomy of woody vines differs from that of trees. In trees, the wood or xylem, of which only the newest and outermost annual ring actually conducts water, is in the form of a solid cylinder whose rigidity is able to support large crowns of leaves and branches. Vines need to be more flexible to cope with the twists and turns of climbing or the stresses that result when they partly or completely slip away from their supports. Woody vines achieve flexibility by having a considerable amount of soft tissue as well as wood in their stems. In some, the cylinder of wood is divided into segments that alternate with soft tissue; in others, there are alternating cylinders of wood and soft tissue. Some woody vines also have flattened, ribbon-like stems to achieve greater flexibility					**0**	
2	Arches provide structural support: termites	The nests of termites gain structural support for chambers, ventilation shafts, and insulating cavities because arches are the main architectural element	"The basic building step in many termites involves gluing fecal pellets to make arches; the arches, supporting a network of other arches, provide most of the structural strength needed to support specialized chambers, ventilation shafts, and insulating cavities, and they supply convenient walkways as well. Recycling feces is a superb way to turn a problem into a solution...The construction of the arches goes well beyond flexibility and variation...Columns are neither too close nor too far apart to permit the subsequent construction of arches."					**0**	
3	Fibers reinforce nests: wasps	Nests and honeycombs of wasps are sturdy because they incorporate fibers in a parallel pattern	Reinforcement by the planned use of fibers, as in fiberglass or ferroconcrete, is also evident in the thin cardboard pillars of wasps' nests and honeycombs. In principle, these pillars consist of the same material as the rest of the structure. However, they derive their great strength from the fact that all the wood fibers are arranged in a parallel pattern. That is to say, the wasps instinctively take into consideration the strength requirements of their building materials while building their nests--and they do so with ingenious simplicity					**0**	
4	Construction pattern forms sturdy tubes: organ-pipe wasp	The nests of organ-pipe wasps are long sturdy tubes built from strands of mud in a herringbone pattern.	"The inch-long female begins at the top with a ball of wet mud and applies it to the vertical surface, stretching it out into ropes braided into a herringbone pattern, creating a ^ built in two steps: first the /, working from bottom to top, then the \, again beginning at the bottom and joining its mirror image at the top."					**0**	
5	Shapes cover curved surfaces efficiently: tortoise	The shell of tortoises optimizes material use for a curved surface via hexagonal subunits and filler shapes	"Inevitably nature is not always exact, despite the precision of the honeycomb. When looking for 120° angles in animal forms it is important to remember another geometric law, which is that flat hexagons will only interlock in a flat plane; they cannot be combined to enclose a space, as can the triangles that constitute the tetrahedron. Where hexagons do occur on curved surfaces -- such as in the beautifully delicate skeletons of some microscopic marine organisms called Radiolaria -- there are always some other shapes and angles inserted to compensate for the curvature. The same is true of the tortoise's shell, where remarkably regular hexagons in the centre are bounded by pentagons (five-sided shapes) which fuse to give a straight edge to the shell; exactly the same happens in insect wings. Three-way junctions also tend to occur where pieces of similar size and shape must be overlapped to cover a surface, as in the feathers of a bird, the scales of a fish, or the scales of a pangolin."					**0**	
6	Filaments adopt geometric symmetry: mammals	The formation and dynamics of the keratin intermediate filaments in mammalian stratum corneum may be the result of membrane templating	"Keratin is tough, adaptable, flexible, resistant to water, and provides a good protective covering for the rest of the body. These qualities also make it an ideal material for the moulding of claws, nails and hooves...					**0**	
7	Leaf serves as container: red oak roller weevil	Female red oak roller weevils create packages to hold their eggs by cutting and rolling oak leaves into tubes	"A weevil, the red oak roller, uses a leaf as a container for its young. It cuts the leaf transversely across the middle to the central rib, working first from one side then the other. It folds together the two quarters nearer the tip over the midrib and then rolls them into a double thickness tube. In that it lays its eggs					**0**	
8	Joints have two degrees of bending freedom: arthropods	The joints of some arthropods have two degrees of bending freedom (up-down and left-right) thanks to two 1-degree bending joints found at right angles to each other	"Bending both up-down and left-right...Arthropods gain two degrees of bending freedom by putting two 1-degree bending joints next to each other, each oriented at a right angle to the other...The classic work on such cases was done by S.M. Manton, in the 1950s and 1960s; as put, with a long list of references, by Wainwright et al. (1976), 'The accounts of her researches in this field constitute a monument in the study of mechanical design of the most mechanically diverse group of organisms that have ever lived.'"					**0**	
9	Skeleton components arranged efficiently: starfish	The skeletons of some echinoderms arrange their calcium carbonate plates efficiently using pentaradial symmetry	"Starfish have five arms; sand dollars have five radial food grooves on their undersides--this arrangement of five elements radiating from a center point ('pentaradial symmetry') is widespread among the echinoderms but unknown elsewhere in nature...Early echinoderms were covered with a skeleton made up of discrete plates of calcium carbonate. Now one can pave a floor with triangles, squares, or hexagons, but using pentagons alone inevitably leaves gaps. One can't make an array of squares close on itself to form a hollow solid unless at eight special locations the apices of three rather than four squares touch, a distinct complication. And one can't make any array solely of hexagons close on itself at all. Conversely one can get a closed, space-enclosing structure from triangles (tetrahedrons are the simplest, but others such as twenty-sided icosahedrons are possible) and pentagons (the simplest being the twelve-sided dodecahedron). Among the pentagons (fig. 4.13) hexagons can be intercalated practically without limit, but twelve basic pentagons must remain. In the most symmetrical arrangement, these pentagons are in six pairs with members of a pair at the opposite extremities of the solid. If we run an axis between members of one pair, the ten other pentagons then arrange themselves in two nearly equatorial rings. If enough hexagons are intercalated, these can form the key elements of five arms. And a look at any book treating the paleontology of echinoderms reveals a host of hexagonal plates. Perhaps a pentaradial symmetry is, in fact, a 'natural' or easy way to organize a radially symmetrical creature built of a shell of little solid elements!"					**0**	
10	Structures optimize material use: plants	Plants maximize strength while reducing materials by incorporating tetrahedral elements that can be stacked in hexagonal containers	"Nature has provided many packaging methods to protect plants and animals against physical impact. The design often uses a minimum of material while offering a maximum of usable space. Tetrahedral elements which can be stacked in hexagonal containers without any waste of space are frequently found in plants."					**0**	

In order to rank the NSoI in order to obtain a smaller set of examples, each NSoI is analyzed and for each parameter is given an evaluation.

The evaluation is done by using a scale of **Levels of Appropriateness** (Vagias, 2006):

- 1 – Absolutely inappropriate
- 2 – Inappropriate
- 3 – Slightly inappropriate
- 4 – Neutral
- 5 – Slightly appropriate
- 6 – Appropriate
- 7 – Absolutely appropriate

The level of appropriateness of each parameter can vary from 1 to 7 and then is multiplied with the importance obtained in with the rank order matrix.

Table 2.4 **Excerpt of an evaluation matrix of all the NSoI concerning the criteria and their importance** (Sutter, 2013)

		Possible NSoI							
Evaluation Criteria	**Importance**	**NSoI 1**		**NSoI 2**		**…**		**NSoI 147**	
Scale of phenomenon	6	6	36	4	24	…	…	1	6
Analogy between industrial example and our problem	2	7	14	4	8	…	…	1	2
Environmental conditions for the NSoI	1	6	6	4	4	…	…	6	6
Physical implementation	3	5	15	5	15	…	…	1	3
		24	**71**	17	**51**			9	**17**

This lead the overall weight of the single natural phenomenon, see second column of every NSoI in Table 2.4. After having evaluated all the results it is possible to select a set of NSoI using the overall weight i.e. the value in bold in the second column of each NSoI obtained due to the comparison.

2.4.3 - The output of Step 3

As output of the step 3, it will be obtained a list of 3 or 4 NSoI. The number of the NSoI selected depends on the designer sensibility and the available time to realize the functional and causal models. The selected NSoI are the most pertinent to the problem regarding the specific features used as parameters during the selection.

With this list of NSoI it is possible to individuate further information such as pictures, text descriptions, and references that can be retrieved in the strategy page of the NSoI selected on AskNature.org

Furthermore, during the pre-selection phase the task of reading the description of the NSoI individuated can enhance the designer's creativity stimulating analogies also with NSoI not completely pertinent to the problem under study.

2.5 - Specification on Step 4 – Definition of the Nature's solution

According to the BID definition proposed by (Vattam, Helms, et al., 2010):

"(…) is *approach to design* that espouses the *adaptation of a function* and *mechanism* in *biological sciences* to solve Engineering Design problems (…)"

The goal of this step is the extrapolation, from the final list of NSoI obtained as output from step 3, of functions and mechanisms i.e. the Nature's solution to use for the Problem-Solving.

In order to achieve this goal the designer can create functional or causal models of the selected NSoI. The models allow a structured representation about how the natural system "works". Moreover, the models provide a standard description of the *Function*, the *Parts*, the *Behaviour*, the *Effects* etc.

Step 4 is supported by a method composed by 4 steps and a tool i.e. the causal and functional models and a set of guidelines extracted by an on-line survey about the perceived meaning of the items of the functional model by Biologists.

2.5.1 - The method

The method proposed in this step allows to properly representing the information about the selected NSoI by means of functional and causal models. Moreover, the method allows to verifying the completeness of the models and helps in the search of extra information if it necessary.

The method is the following:

i. Describe by means of functional or causal models the selected NSoI
ii. Verify the completeness of the models i.e. presence of information in all the items of the model
iii. Search, if necessary, extra information:
    a. Paper based - internet search
    b. Interaction with a Biologist
iv. Revise the model(s) of the NSoI

2.5.2 - The tools

The SAPPhIRE or the DANE modelling approaches are the main tools for carry out this step. These two models allow describing with a standard engineering view the NSoI. Moreover, the information represented by the models can be easily understood and used by designers. In fact, the availability of the information allows an easy extraction of the natural knowledge during the design phase.

The step starts with the information modelling in order to create a structured representation of the natural knowledge about the natural phenomenon.

Furthermore, a set of guidelines is provided to guide the designer both in the modelling part and in the search for extra information necessary for the complete understanding of the phenomenon.

2.5.2.1 The Functional and Causal model representation

For the representation of the selected NSoI, it is possible using either the SAPPhIRE or the DANE modelling approaches.

In order to show the different perspectives of the two modelling approaches in this section is presented an example of a Bio-Inspired product selected from literature beyond the papers on DANE and SAPPhIRE. Both the natural source of inspiration and the technical system produced through this Natural Source of Inspiration have been modelled with the two modelling approaches. As a result, it is possible to appreciate the complementary characteristics of the information they can represent.

The selected case study is the micro-fluidic device, which is capable to "separate leukocytes from whole blood" (Shevkoplyas, Yoshida, & Munn, 2005) represented in Figure 2.11 (a). This device relies on natural phenomena known as plasma skimming and leukocyte margination. In fact, it closely imitates the blood microcirculation and consists in a "network of rectangular micro-channels designed to enhance the lateral migration of leukocytes and their subsequent extraction from the erythrocyte-depleted region near sidewalls". This device guarantees a continuous flow, provided by a small pressure gradient that supports the flow of blood.

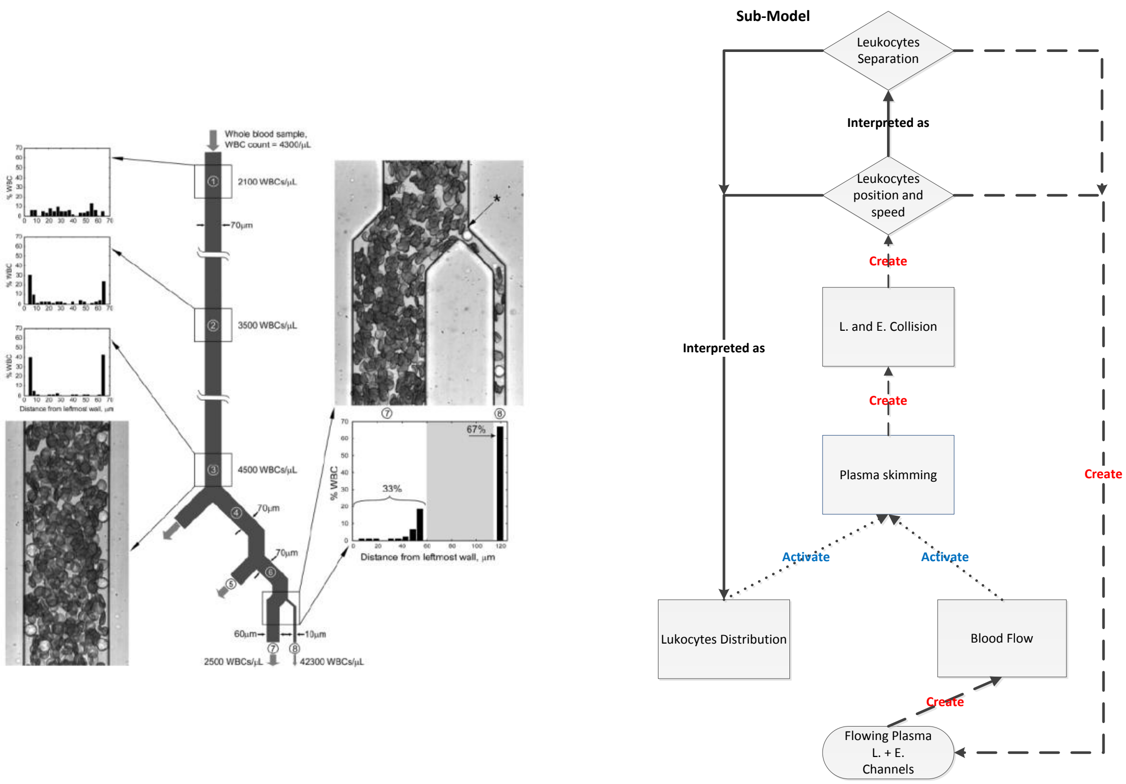
Since erythrocytes are smaller and more deformable with respect to leukocytes, they "tend to flow at the centre of blood vessels, leaving a plasma-rich zone adjacent to the vessel wall; they also flow faster than leukocytes". This behaviour "encourage collisions" between leukocytes and erythrocytes, which result in an enrichment in leukocyte of the zone close to the vessel wall. A portion of the blood richer in leukocyte can be then extracted from the main flow, forcing the blood to flow through an asymmetric bifurcation. The whole process can be seen as a repetition of two main phases: firstly, leukocyte naturally migrates towards the wall; secondly, the layers near the wall are extracted from the main flow by means of asymmetric bifurcations.

Figure 2.11 (b) shows the SAPPhIRE model of the leukocyte lateral migration phenomenon. A uniform distribution of leukocytes and erythrocytes *"Input"* in the blood *"Part"* flowing in a micro-channel *"Part"* activate collisions *"Physical phenomenon"* between leukocyte and erythrocyte, thanks to plasma skimming *"Physical effects"*. This results in a change of leukocyte distribution *"State"*. The complete process is known as leukocyte margination.

Figure 2.12 shows the three main parts of the DANE model. In particular, Figure 2.12 (b) shows the *"Behaviour"* model of the whole process of the device. The two subsequent phases as well as their correlation can be easily identified. The representation of a two phases process in SAPPhIRE requires at least two instances of the model (one for each phase), while in DANE it is possible to add as many states as needed. Therefore, the two phases can be represented in a unique instance of the model.

Comparing these two representations, the SAPPhIRE approach appears to be more suitable to highlight the causal relations in the system. Furthermore, it is somehow more flexible, allowing the user to represent information at a higher abstraction level. On the other hand, the DANE schema embeds an explicit representation of the sequence of state changes that occurs in the overall process, highlighting the physical parameters involved in each of them. On the contrary, the instances of the SAPPhIRE schema, which represent different phases of the same process, cannot be correlated directly and explicitly. In the SAPPhIRE model, *"State"* and *"Action"* are only connected to the *"Input"* of the same diagram (i.e. the same phase of the process).

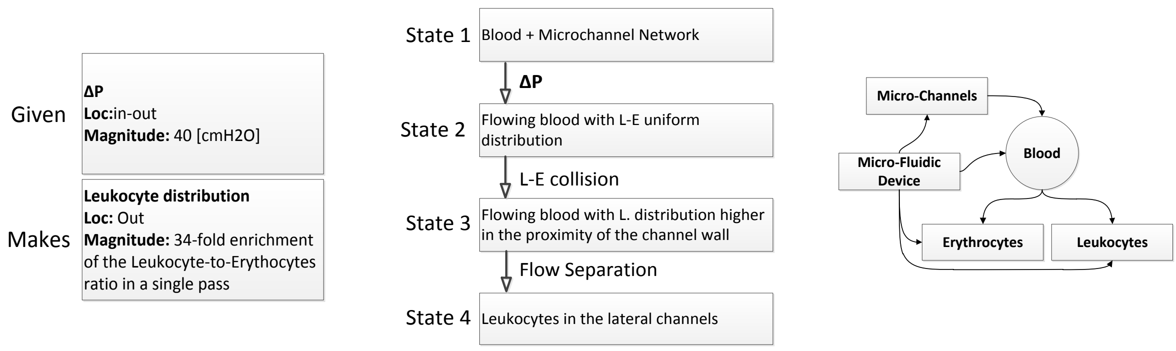
Figure 2.11 A (a) Micro-fluidic device schema; (b) SAPPhIRE model of leukocytes separation



(a) (b)

Let us consider the blood flow generation because of a pressure gradient (Bernoulli Effect) as an example. The pressure gradient is required to generate the flow, but it is generated by an external device, and therefore it cannot be interpreted as a consequence of any action or of any physical phenomenon of the process. A similar situation occurs in the den of prairie dog (Sartori et al., 2010), where the pressure gradient *"Input"* is generated by the wind [external phenomenon] and not by den ventilation *"Action"*. Finally, in SAPPhIRE, system and environment parts are listed altogether in a unique field, which is connected to the *"Organ"* field only. Besides, the DANE model includes a structure representation that allows to explicitly describing the structural relationships among the parts Figure 2.12 (c).

Figure 2.12 Function (a), Behavior (b) and Structure (c) models according to DANE



(a) (b) (c)

Modelling example extracted by (Baldussu et al., 2012)

2.5.2.2 The guidelines extracted from the on-line survey

For step 4, the method involves a set of guidelines extracted from a survey on the perceived meaning of the models items by Biologists.

The survey has been aimed by the attempt to better understand how biologists perceive the definitions and the name of the items of the models usually used by designers i.e. the SAPPhIRE and the DANE models. An on-line survey has been specifically developed for the purpose.

In order to reach a bigger number of biologists, the survey's link has been divulgated by two distribution channels.

The first one is a newsletter service that has been sent to all the members of the Faculty Promotion List of WZW - Wissenschaftszentrum Weihenstephan of the Technische Universität München (Centre of Life and Food Sciences Weihenstephan - TUM). Approximately 1.000 people, which appertain to all the fields of Biology and Natural Sciences, compose the list.

Moreover, the survey's link has been sent to all the teachers of the Biology faculty of the University of Florence that is composed by circa 60 teachers.

In order to obtain a consideration on the response rate it is possible to that the Survey's link has been received by approximately 1.000 people.

A total of 30 Biologists have submitted completely the survey that means a response rate of **≈ 3%**

The survey took approximately 15-20 minutes to be completed and there were 19 questions in total and has been structured in three main sections.

The complete set of question is reported in the Appendix G.

The survey has been structured as follows:

1. Generic questions about the fundamental information for a biological description of a natural system
2. Questions about the meaning in biology of the characteristic terms of the causal and functional models
   - ✓ What is an action in biology? – i.e. "*action" is the name of a SAPPhIRE's model item*
3. Questions about the terms a biologist would use for the SAPPhIRE and DANE item's definitions
   - ✓ How would you "label" the following definition: A physical variable that crosses the system boundary, and is essential for an interaction between the system and its environment

In order to understand how the questions provided in the survey allow improving the BID design a couple of examples of them are given:

Which definition would you give to the following Name-Label?

Name-Label: Action.

The answers help in understanding similarities and differences between the information used by Biologists in describing natural phenomena and Engineers while accomplishing functional or causal modelling.

Which Name-Label would you give to the following definition?

Definition: A physical variable that crosses the system boundary, and is essential for an interaction between the system and its environment.

The information extracted by the answers is fundamental to improve the communication between Designers and Biologists especially in the design phase when it is necessary to deepening the understanding about the natural phenomenon.

Analysing the survey's results two sets of guidelines have been developed.

2.5.2.2.1 Guidelines to improve the modelling capabilities of Designers

The first set of guidelines is aimed at improving the modelling capabilities of the technicians while modelling the NSoI by functional or causal models.

i. In order to fulfil the models when you are searching in the Biological documents consider the following indications

- The terms **Structure/Part** could be describe as a synonymous
- The terms **Structure/Part** could be called object
- The term **Function** could be interpreted as the goal of the system
- The term **Effect** has a completely different definition in Biology

ii. When searching for the natural information to fill out the functional and causal models verify in Table 2.5 *how the information which you are interested could be interpreted or represented by Biologists*

Table 2.5 Matrix of correspondence between the Engineering labels of the functional and causal models and the Biological interpretation

Engineering label	Definition	Biologists could interpret or represent as:
Input	*a physical variable that crosses the system boundary, and is essential for an interaction between the system and its environment*	Physical Phenomenon
Effect	*a principle of nature that underlies and governs an interaction*	No correspondence
State	*a property of the system (or its environment) that is involved in an interaction*	Organ
Part	*a set of physical components and interfaces that constitute the system of interest and its environment*	Structure
Organ	*a set of properties and conditions of the system and its environment required for an interaction between them*	State
Action	*an abstract description or high-level interpretation of an interaction between the system and its environment*	Model
Physical Phenomenon	*an interaction between the system and its environment*	Action
Structure	*the elements of the natural system, the material arrangement of these elements and their connectivity*	Part
Behaviour	*the natural system's action or processes in given circumstances of the natural environment*	Behaviour
Function	*the results of the natural system's behaviours*	Goal

2.5.2.2.2 Guidelines to improve the communication between Biologists and Designers

The second set of guidelines has been provided for when the research in the Biological literature is not sufficient for complete understanding of the natural phenomenon and is necessary in a biological advice

When talking with an expert Biologist, in order to have some details about the Natural Phenomenon, the following set of criteria should be taken into consideration.

iii. *In order to deepen the understanding of the Natural phenomenon under study for your Bio-Inspired Product during a consultancy consider that:*

- The terms **Action** could be interpreted as **Model**
- **Model** is a critical concept for biologist
- Use the OED Definitions for the terms while talking about:
    - **Action**
    - **Behaviour**
    - **Input**
    - **Organ**
    - **Part**
    - **Structure**
- Use the OED Definitions for the terms adding some examples while talking about:
    - **Function**
    - **Physical Phenomenon**
- Pay extreme attention using the term **Effect**, probably each Biologist have a specific field definition for this term that could be drastically different from the engineering definition

In Table 2.6 it is reported the level of acceptance of the OED definitions by the biologist that have submitted the survey. The Oxford English Dictionary definitions can be used as a facilitator for the discussion in order to avoid misunderstandings.

Table 2.6 Oxford English Dictionary definitions of the causal and functional models items' labels

Label	Oxford English Dictionary Definition	Appropriate	Slightly a/(ina)ppropriate
Action	*Something done or performed, a deed, an act; (in pl.) habitual or ordinary deeds, conduct.*	70%	
Behaviour	*The manner in which a thing acts under specified conditions or circumstances, or in relation to other things*	70%	
Effect	*The physical result of the action of a force*		40% - 40%
Function	*The action of performing; discharge or performance of (something)*	60%	30%
Input	*That which is put in or taken in, or which is operated on or utilized by any process or system*	90%	
Organ	*Any of various mechanical devices or A part of an animal or plant body that serves a particular physiological function*	80%	
Part	*A piece or section of something which together with another or others makes up the whole*	90%	
Physical Phenomenon	*Of or relating to natural phenomena perceived through the senses (as opposed to the mind); of or relating to matter or the material world; natural; tangible, concrete - A thing which appears, or which is perceived or observed.*	60%	20%
State	*The combination of circumstances or attributes belonging at a particular time to a person or thing; a particular manner or way of existing as defined by the presence of certain circumstances or attributes; a condition*	70%	
Structure	*The mutual relation of the constituent parts or elements of a whole as determining its peculiar nature or character; make, frame*	70%	

2.5.3 - The output of Step 4

As output of the step 4, it is obtained a set of causal or functional models, depending on the modelling approach chose by the designers, of the NSoI selected using the criterion and the parameters appropriate to the technical problem.

The models are a structured description of the selected NSoI that is composed by the following information:

- Function (Action, Input & State)
- Behaviour (Effect and Physical Phenomena)
- Structure (Organ and Parts)

According to the comparison between the two modelling approaches i.e. SAPPhIRE and DANE proposed in (Srinivasan et al., 2012b) in the above list the parenthesis represent the items of the SAPPhIRE model.

2.6 - Specification on Step 5 – Principles extraction

Once obtained a structured description of the selected NSoI by means of functional or causal models it is necessary to guide the designer in the extraction of the useful natural information to use in the design phase in order to solve the technical problem. For this step, a set of guidelines obtained by the analysis of a sample of BIPs is provided.

2.6.1 - The Guidelines extracted from the BIPs analysis

In order to understand which natural information has been implemented in the BIPs it has been analysed a set of Bio-Inspired concepts and products that use Nature as a Source of Inspiration. The collection of BIPs has been made extracting randomly 30 scientific papers, from the BID literature, which deals with the solution of technical problems due to the implementation of natural strategies. According to the classification proposed by (Hubka & Eder, 1988) the selected case studies are characterized by a level of complexity which vary from *Level 1* (i.e. Part, Component - Elementary system produced without assembly operations) to *Level 3* (i.e. Machine, Apparatus, Device - System that consists of sub-assemblies and parts that perform a closed function).

Features of the BIPs' sample

- Number of BIPs: *30*
- Level of complexity: *Levels I, II and III*
- Sources: *Scientific papers and Books about Bio-Inspired Design*

Models used to describe the NSoI and the correspondent BIPs

- SAPPhIRE
  - *Natural Source of Inspiration – NSoI*
  - *Implemented Solution – BIP(x)*
- DANE
  - *Natural Source of Inspiration – NSoI*
  - *Implemented Solution – BIP(x)*

Others BIPs' features analyzed

- Type of problem: *described using the NIST Functional Basis*
- Type of transfer: *classification proposed by* (Mak & Shu, 2004)

- Type of main natural feature implemented in the BIP: *according to the classification of the properties of the system proposed by* (Eder & Hosnedl, 2007)

In order to be able to compare the information content of a set of different Bio-Inspired concepts and products it has been necessary to individuate a tool, which allows to realize a standard description of a certain amount of information i.e. the text which describes the Natural Source of Inspiration and the text which describes the Bio-Inspired Product. The most appropriate tools in order to carry on this task are the causal or functional models. In this research, we decide to use both, the SAPPhIRE and the DANE, which are the most diffused models in the field of BID.

For each case study has been applied the following procedure:

1. *Representation of the information about the Natural Source of Inspiration (NSoI) by means of both the SAPPhIRE and the DANE modelling approaches*
2. *Representation of the information about the Bio-Inspired Product (BIP) by means of both the SAPPhIRE and the DANE modelling approaches*
3. *Comparison between the model(s) of the NSoI and the model(s) of the BIP for:*
   3.1. *SAPPhIRE model(s)*
   3.2. *DANE model(s)*
4. *Check if all the necessary information, for a comprehensive description, is represented by means of the models*
5. *Cluster of the information represented in the models and the eventual extra information necessary for the description of the case study:*
   5.1. *Function (Action, Input and State)*
   5.2. *Behavior (Effect, Physical phenomenon)*
   5.3. *Structure (Organ and Parts)*
   5.4. *Properties*

Table 2.7 presents a synthetic view of the results extracted from the analysis of the case studies.

Table 2.7 Case Studies analysis: Comparing information contents with SAPPhIRE and DANE models and list of Properties

CS #	Natural Source of Inspiration	Bio-Inspired Products	SAPPhIRE	DANE	Cluster	Description	Internal vs External	Class	Sub-Class
1	Plasma Skimming - Leukocite Migration	Biomimetic Autoseparetion	≈R; I; Ph; E; S; ≈A	≈F; ≈B	≈F; B	Use of the natural principle and adaptation	Internal Properties	Pr10 - Engineering design characteristics	
2	DNA Relase	Handling Microparts	-	-		Copy of the overall gripping idea	External Properties	Pr12 - Elementar engineering design properties	
3	Abscission Process	Assembling Microparts	A	F	F	Adaptation	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
4	Taenia Solium -Tapeworm	Specific purpose locomotion system	≈P; R; Ph; E; S; A; I	F; B	F; B; ≈S	Copy of the function: approach	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
			≈P; R; Ph; E; S; A; I	F; B	F; B; ≈S	Copy of the function: attach	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
5	Fibrillar Features	Gecko-Like Adhesion	≈P; ≈R; Ph; E; A; I	F; B	F; B; ≈S	Scaling up a microscopic features	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
6	Cicada wings	Coating material	P; R; Ph; E; S; A; I	F; B; ≈S	F; B; S	Copy of the function: Transparency	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
			P; R; Ph; E; S; A; I	F; B; ≈S	F; B; S	Copy of the function: Self-Cleaning	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
7	Natural Functional Surfaces	Bioinspired Actuated Microstructure	A	F	F	Use of the natural features: responsive behaviour	Internal Properties	Pr10 - Engineering design characteristics	
			A	F	F	Copy of the function: Self-Cleaning	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
8	Wood wasp	Planetary and Earth drill	≈P; ≈R; Ph; E; S; A; I	F; B; ≈S	F; B; ≈S	Copy of the overall drilling idea	Internal Properties	Pr12 - Elementar engineering design properties	
9	Neuron	Bio-Physically Inspired Silicon Neuron	≈P; ≈R; Ph; E; S; A; I	F; B; ≈S	F; B; ≈S	Copy of the natural principle	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
10	Solar Water Oxidation	Solar Hydrogen production	Ph; P; S; ≈I; ≈A	≈F; B	≈F; B	Copy of the chemical process	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
11	Jellyfish	Fuel-powered SMA veichle	≈P; E; S; A	F; B; ≈S	F; ≈B; ≈S	Reproduction of a natural propulslion system	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
12	Parasitoid Ormia ochracea	Omnia-inspired microphones	≈P; ≈R; Ph; E; ≈A	≈F; B; ≈S	≈F; B; ≈S	Use of a natural strategy	Internal Properties	Pr10 - Engineering design characteristics	
13	Dung bettle	Ternary Coupling Bionic Bit	≈P; ≈R	-	≈S	Copy of a surface features (morphology)	Internal Properties	Pr10 - Engineering design characteristics	
14	Gecko-feets	Carbon Nano-Tube Self Cleaning Adhesive	P; R; Ph; E; S; A; I	F; B; S	F; B; S	Copy of a surface features (morphology)	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
			P; R; Ph; E; S; A; I	F; B; ≈S	F; B; S	Copy of the function: Self-Cleaning	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
15	Root network	Nature's symmetries	≈P; R	≈S	≈S	Copy of spatial distribution - Configuration	Internal Properties	Pr12 - Elementar engineering design properties	
16	Tumbleweed	Veichle for planetary surface exploration	≈R; Ph; E; S; A; I	F; B	F; B	Use of the same imput whith the same Shape	Internal Properties	Pr12 - Elementar engineering design properties	
17	Vertebral column	Shape morphing structures	E	≈F	≈F	Imitation of the averall morphology	Internal Properties	Pr12 - Elementar engineering design properties	
18	Wonding	Bio-Inspired Watch	A	F	F	Copy of the function: Self-Reparing	External Properties	Pr1 - Purpose Properties	Pr1C- Operational properties
19	Lotus surface	Lotusan® paint	P; R; Ph; E; S; A; I	F; B; ≈S	F; B; S	Copy of a surface features (morphology)	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
20	Burdock seed	Velcro ®	P; R; Ph; E; S; I	B; S	B; S	Copy of a surface features (morphology)	Internal Properties	Pr12 - Elementar engineering design properties	
21	Venus flytrap + night-blooming cactus	Cable entry system	R; Ph; E; S; ≈I	F;B	F; B; ≈S	Copy of the Behaviour - Closure system	External Properties	Pr1 - Purpose Properties	Pr1B - Functionally determinated propeties
			O	-	-	Copy of the Configuration - Leafs overlapping and shape			
22	Muscle	Electro Active Polimers	≈I; A; ≈S	≈F	F	Copy of the function: produce force/motion	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
23	Ants	Autonomous rounting in Flexible Manufacturing Systems	≈S; ≈A	-	F	Copy of the strategy: ant colonie cordination	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
24	Rainbow trout	Fin with Bio-Inspired stiffness profile and geometry	P; R; Ph; E; S; A; I	F; B; ≈S	F; B; ≈S	Copy of Design propertyes (stiffness and morphology)	Internal Properties	Pr11 - General engineering design properties	
25	Torax cage	Structural Bionic Design	Ph; E; S; A; I	F;B	F; B	Copy of the ribs disposition (Configuration)	Internal Properties	Pr11 - General engineering design properties	
	Stem		Ph; E; S; A; I	F; B; ≈S	F; B; ≈S	Copy of the internal morphology			
26	Caterpillar	Modular wall-climbing caterpillar	E, Ph, A	F; B; S	F; B; ≈S	Copy of the Kinematics	Internal Properties	Pr10 - Engineering design characteristics	
			-		F				
27	Rodent's teeth	Self-Sharpering Cutting Tools	≈O	-	≈S	Copy of a surface features (internal morphology)	Internal Properties	Pr11 - General engineering design properties	
28	Sandfish (Desert Lizard, Laudakin stoliczkana)	Abrasion resistance	≈P; ≈R; Ph; E; S; A; I	F; B; ≈S	F; B; ≈S	Copy of a surface features (morphology)	Internal Properties	Pr11 - General engineering design properties	
29	Dragonfly	Corrugated Airfoil	≈P; R; Ph; E; S; A; ≈I	F; B; ≈S	F; B; ≈S	Copy of morphology, configuration and dimensions	Internal Properties	Pr12 - Elementar engineering design properties	
30	Woodpecker	Shock-absorbing system	≈O; Ph; E; ≈A; ≈I	≈F; B; ≈S	≈F; B; ≈S	Copy of dimensions, density, meterial and morphology	External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties

Table 2.8 Case Studies: List of references

CS Nr.	Reference	CS Nr.	Reference
1	(Shevkoplyas et al., 2005)	16	(Antol, 2005)
2	(Shu, Hansen, Gegeckaite, Moon, & Chan, 2006)	17	(Elzey, Sofla, & Wadley, 2003)
3	(Shu et al., 2006)	18	(Stauffer, Mange, Tempesti, & Teuscher, 2001)
4	(Menciassi & Dario, 2003)	19	(Sto Corporation, n.d.)
5	(Bartlett et al., 2012)	20	(De Mestral, 1961)
6	(Naik et al., 2003)	21	(Bar-Cohen, 2012a)
7	(Sidorenko, Krupenkin, Taylor, Fratzl, & Aizenberg, 2007)	22	(Bar-Cohen, 2005)
8	(Gouache, Gao, & Gourinat, n.d.)	23	(Berger & Sallez, 2006)
9	(Farquhar, 2005)	24	(Salumäe & Kruusmaa, 2011)
10	(Brimblecombe, Koo, Dismukes, Swiegers, & Spiccia, 2010)	25	(Zhao, Chen, Ma, & Yang, 2008)
11	(Tadesse et al., 2012)	26	(Wang & Wang, 2011)
12	(Miles & Hoy, 2006)	27	(VDI 6220, 2012)
13	(Gao et al., 2008)	28	(Huang, Zhang, & Ren, 2012)
14	(Sethi, Ge, Ci, Ajayan, & Dhinojwala, 2008)	29	(Hu & Tamai, 2008)
15	(Coppens, 2005)	30	(Yoon & Park, 2011)

As a first step of the analysis, all the models of the NSoI and the BIP of each Case Study have been compared. Table 2.11 in the column SAPPhIRE and DANE shows the results of the above-mentioned comparison. A partial information transfer of a specific item of the model has been indicated with the symbol *(≈)*.

The symbol *(-)* indicates the absence of information transfer if none correspondence has been individuated comparing the models of the NSoI and the BIP.

The column named *Cluster* indicates the correspondence between the SAPPhIRE and the DANE models according to the comparison proposed by (Srinivasan et al., 2012b). In order to avoid the bias related to the differences in the perspective of the two models, it is worth to note that, a match between a specific category of the cluster i.e. *Function*, *Behaviour,* and *Structure* has been assigned only if both models, SAPPhIRE and DANE with their items represent the correspondent above-mentioned category.

Finally, it is important to note that in some case studies more than one Natural Phenomenon or Effect composes the Natural Source of Inspiration and this is reported in the table by the presence of two rows for the same case study.

Furthermore, in Table 2.11 is also presented the comparison between the main natural feature of the Bio-Inspired Product implemented, using the information extracted from the NSoI, and the list of properties proposed by (Eder & Hosnedl, 2007).

According to the comparison, between the information transferred from the NSoI*(i)* to the BIP*(i)*, presented in Table 2.11 it is possible to note that there are some examples where the causal and functional models are not capable to completely represent all the necessary natural information implemented in the Bio-Inspired Product. Usually this information is related to the representation of the *morphological aspects* of the NSoI that are not sufficiently considered in the technical models used in the BID field.

A further analysis shows that, the *Function* is the only part of biological information that can be implemented individually. There are no examples of individually implementation of the *Behavior* but it is always implemented in combination with the *Structure* or with the *Function*.

Table 2.9 Internal vs External Properties implemented in the BIPs

	Implemented items	
External properties	11	32%
Internal Properties	23	68%

According to the results presented in Table 2.9 the information about the internal properties is highly implemented respect to the external one, *68%* of the total. Within the internal properties, there is a strong imbalance between the sub-classes of the properties.

It is worth to note that not all the properties of the technical products presented in the (Eder & Hosnedl, 2007) approach are used in the development of BIPs. In Table 2.10 it is reported the complete list of the properties used.

Table 2.10 Properties used in the development of BIPs

External Properties	Pr1 - Purpose Properties	Pr1A - Function properties, Effect properties
		Pr1B - Functionally determinated properties
		Pr1C- Operational properties
Internal Properties	Pr10 - Engineering design characteristics	
	Pr11 - General engineering design properties	
	Pr12 - Elementar engineering design properties	

Furthermore, Table 2.11 shows the distribution of the classes of properties implemented in BIPs.

Table 2.11 Case studies comparison: biological information implemented in BIPs classified by Properties classes

Pr1 - Purpose Properties	18	53%
Pr2 - Manufacturing, other organization properties	0	0%
Pr3 - Distribution properties	0	0%
Pr4 - Liquidation properties	0	0%
Pr5 - Human factors properties	0	0%
Pr6 - Technical system factors related properties	0	0%
Pr7 - Environmental factors related properties	0	0%
Pr9 - Management, economics, societal and goal factor properties	0	0%
Pr10 - Engineering design characteristics	5	15%
Pr11 - General engineering design properties	4	12%
Pr12 - Elementary engineering design properties	7	21%

Table 2.12 presents the results related to the sub-classes of the properties.

Table 2.12 Case studies comparison: biological information implemented in BIPs classified by Properties sub-classes

Pr1A - Function properties, Effect properties	16	89%
Pr1B - Functionally determinated properties	1	6%
Pr1C- Operational properties	1	6%

Table 2.12 shows that the *89%* of the properties appertains to the **Pr1A** - *Function properties, Effect properties class*.

Table 2.13 presents the results of the final clustering about the biological information implemented in the BIPs. In this table does not appear any information related to the specific modelling tool i.e. SAPPhIRE and DANE. The first four columns are obtained analysing which classes of the cluster have been implemented. It is important to note that in almost the totality of the examples of BIPs has been implement a combination of the biological information appertaining at more than one class of the cluster.

Table 2.13 Cluster of comparison: Natural Information implemented in BIPs represented by the cluster categories

Function	Behaviour	Structure	Properties	Property only
22	18	11	25	**2**
59%	49%	31%	68%	**5%**

A specification on the last column in Table 2.13 is mandatory because it is possible to find BIPs that implement only some specific property i.e. the *Morphology*.

Table 2.14 Single and combined classes of information implemented in BIPs

Function	5%
Behaviour	0%
Structure	3%
Morphology	19%
Function + Behaviour	16%
Function + Structure	0%
Function + Morphology	0%
Behaviour + Structure	14%
Behaviour + Morphology	0%
Structure + Morphology	3%
Function + Behaviour + Structure	35%
Function + Behaviour + Morphology	5%
Behaviour + Structure + Morphology	11%
Function + Behaviour + Structure + Morphology	30%

Table 2.14 presents the results of the analysis that has been conducted in order to individuate how the classes of information are implemented in the BIPs. In the first part of the table it has been analysed the implementation of a single class of information. Then in the second part the combination between the two classes of information. The third part presents the combination of the three classes of information and finally the last row presents the examples that present the implementation of all the information classes.

A further analysis has been conducted in order to understand the design output of the BIPs. According to (Howard, Culley, & Dekoninck, 2008) the design output following the (Pahl et al., 2007) approach can be classified as presented in Table 2.15

Table 2.15 Design output in the (Pahl et al., 2007) **according to** (Howard et al., 2008)

Approach	*Most original*	→		*Least original*
	Behaviour	Functional	Structural	Incremental
(Pahl et al., 2007)	Original (B)	Adaptive (F)	Variant (S)	X

Applying the above-mentioned classification to the case studies it has been possible to obtain the design outputs of the BIPs presented in Table 2.16. It is worth to note that for each case study has been chose only the highest level of originality i.e. if both Behaviour and Function information have been implemented the BIP's design output has been considered an original one.

Table 2.16 Type of output design according to (Howard et al., 2008)

Adaptive (F)	70%
Original (B)	27%
Variant (S)	3%

Finally, according to the classification proposed by (Mak & Shu, 2004) the implementation of the NSoI in the BIPs has been analysed and follows the distribution presented in Table 2.17

Table 2.17 Implementation of the NSoI in the BIPs according to (Mak & Shu, 2004)

Analogy	70%
Anomaly	30%
Biological Transfer	0%
Literal Implementation	0%

The output of the above mentioned case study analysis is the following set of **Guidelines:**

i. *During the principles extraction use the following criteria*

- If for your problem it is necessary implementing the **Function** of the NSoI, in BIPs is usually implemented together with other classes of information
- The **Function**, the **Structure** and the **Morphology** can be implemented singularly to solve a specific problem or sub-problem
- The **Behaviour** is the only class of information that is never implemented singularly
- The **Morphology** can be implemented also only in terms of proportions

ii. Design output considerations

- Implementing only the **Function** usually is obtained a "technical implementation" of the Nature's solution
- Implementing the **Behaviour** usually is obtained a more innovative Bio-Inspired Conceptual Solution
- Implementing the **Structure** usually is obtained an adaptive design

It is important to note that the implementation of the **Morphology** sometimes leads to a very innovative Design. Because the external characteristics of the natural phenomenon takes advantage of the process of Trial & Error imposed by the evolutionary needs. This aspect characterizes the high level of efficiency of natural system that is the result of millions of years of evolution and it is worth taking advantage of this refinement because it is not possible reproducing in industry.

2.6.2 - The output of Step 5

As output of step 5, it will be obtained the natural information about the Nature's solutions of the selected NSoI to use in the last step of the methodology i.e. the Design phase.

After a first stage of improving the understanding of the Natural Phenomena, that leads to the completion of the causal and functional models, the application of the guidelines allow selecting the most relevant natural information for the development of the conceptual solution.

The selected natural information will be the input for the design phase and can be freely applied according to the designer's sensibility and design characteristics.

2.7 - Definition of an integrated causal-functional model for the Step 4 – Definition of Nature's solution

As has been widely discussed in the previous chapters among the BID modelling approaches available in literature, DANE and SAPPhIRE certainly share the greatest attention for both the consistency and the regularity of their development over the years. Besides, these models cannot be considered as alternative frameworks, since they are characterized by substantially complementary characteristics. In fact, the SAPPhIRE model presents a holistic perspective in the representation of both the natural and the technical systems. On the other hand, the DANE modelling approach gives a detailed description of system internal structure.

Anyhow, in the scientific literature, it is possible individuating examples of Bio-Inspired Products where the information concerning the Natural Source of Inspiration cannot be represented neither with the SAPPhIRE model, nor with the DANE model.

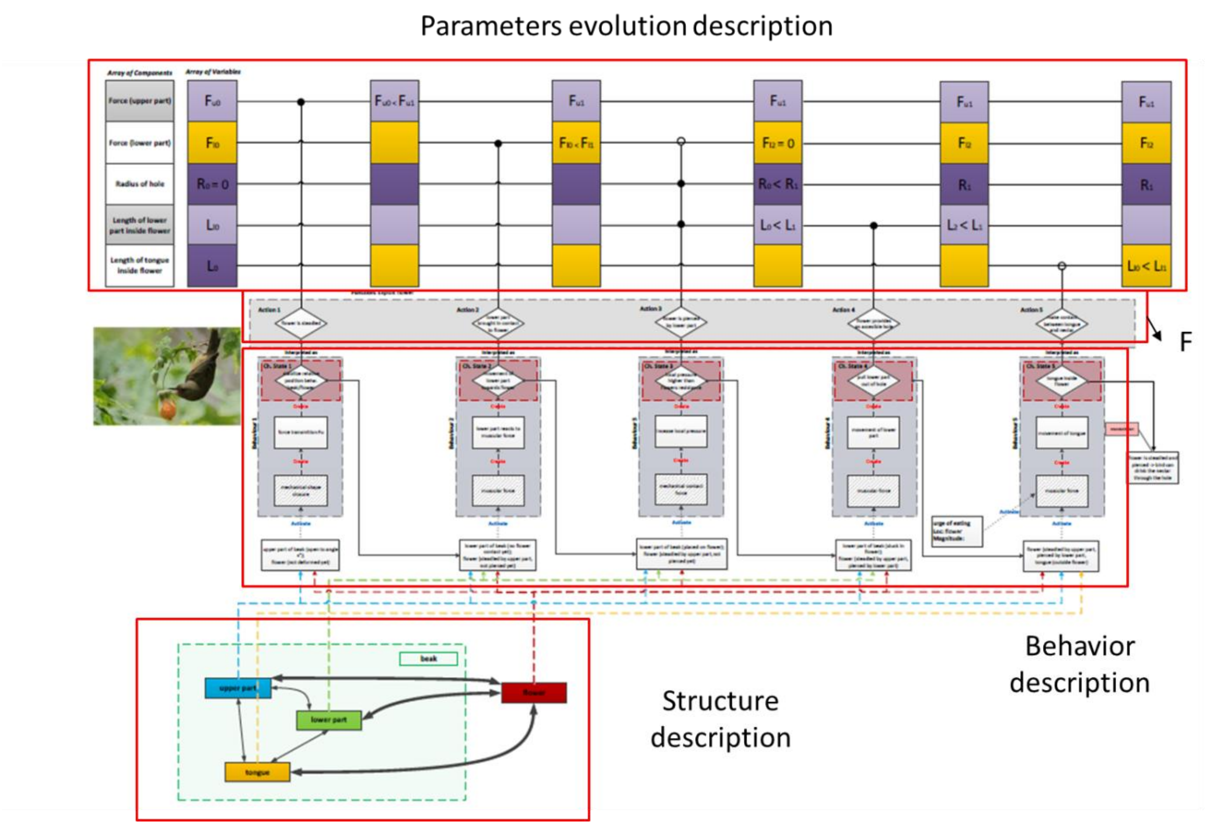
In (Baldussu et al., 2012) it has been proposed a systematic comparison of DANE and SAPPhIRE ontologies, which demonstrated that these models present some semantic gaps, but no conflicting definitions or relationships.

(Baldussu, Cascini, & Rosa, 2013) in their paper conclude that these models are not two alternative frameworks; even more, they are substantially complementary and, as such, can be used as constituent references for an integrated, comprehensive model for BID activities. SAPPhIRE is mainly conceived to represent the causal chain from phenomena to action, while DANE main scope is a clearer representation of system *Behavior*, *Structure* and state transitions.

In the conceptual design stage of a BID approach, a designer needs both these information, it is worth building a model that embeds all this information. The integrated model, proposed by the author and used as a modeling tool during this research, has the ability to represent the information about the:

- Structure
- Behavior
- Function
- Evolution of the parameters involved in the Natural Phenomenon

Figure 2.13 Representation of the integrated SAPPhIRE-DANE model (Sutter, 2013)



The aim of the model is that create a description of the NSoI that allows correlating a single component of the system directly to the parameters. This "red line" of description starts from the component, passing through the behavior until reaching the correlated sub-function.

The *Input* combined whit the *Part's features* activates the *Physical Effects* which creates a *Physical Phenomenon*. The *Physical Phenomenon* creates a *Change of State* that can be interpreted as a *Sub-Function* of the system. To each *Sub-Function,* it is related one or more modification of the *Parameters* involved in the natural phenomenon and this changes can be *Desired* or *Undesired*.

In the first case, the connection will be represented with a *Solid Dot*; on the other hand, the *Undesired* change will be represented by an *Empty Dot*.

A *Sub-Function* or a set of them can create a higher level *Function* of the *Component* or the *Sub-System* under analysis. All the *Sub-Functions* together with the *Functions* will create the *Action* of the system.

2.7.1 - The Structure's description

Both models i.e. SAPPhIRE and DANE have a lack in the description of the structure due to two main reasons. In the former, the description of the structure of the system is a simple list of *Parts*. In the latter also if the description of the parts is more complete, because there are indication about the connection and the interaction among them, it is not clearly and univocally indicated *how the parts interact* and *which kind of interactions* are possible.

This problem has been resolved in many fields of Biology, (Wagner, 2001):

> *[…] Phylogenetic systematics is mainly interested in the homology of parts (and of their attributes), functional anatomy is interested in how parts interact to perform tasks, and studies of morphological and functional complexity are concerned with numbers of different types of parts in organisms. In these areas, [Biologists] typically identify parts using precognitive perceptual mechanisms, or gestalts. The success of the analyses ordinarily leaves little reason to doubt that these gestalts are highly reliable, that the parts identified are biologically significant features of organisms. Also, in these areas, we can often choose parts opportunistically, incorporating into our analyses only structures, which would be recognized as parts by any observer, the uncontroversial parts. […]*

This approaches shows that Biology have already solved the problem of describing the structure and the representations proposed in the Biological models for this purpose are superior respect to the technical description adopted in BID approaches.

First, it is fundamental understand the biological definition of **Part**:

A part is a system that is both integrated internally and isolated externally (Wagner, 2001)

The integration refers not just to bonds between components but also to any interactions that produce correlation in the behavior of the components.

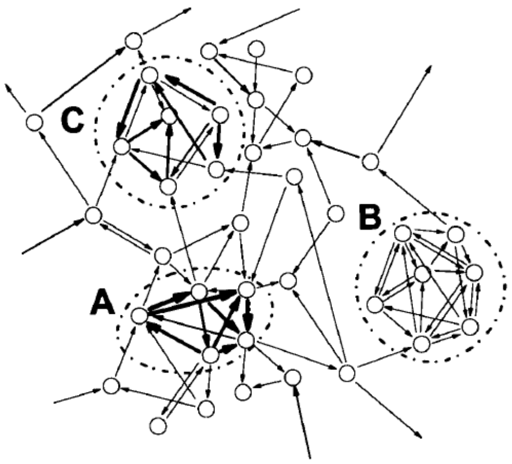
The interaction can take the form of a signal and can be characterized by the:

- Number
- Entity
- Combination of number and entity

For the purpose of the description, it is assumed that we consider systems that have *interaction-based Parts*.

Figure 2.14 represents Parts, Components and interaction among them. Small circles are components and the arrows show the interaction. The thickness of the arrows corresponds to the strength of interaction. It is important to note that dashed lines enclose the Parts.

Figure 2.14 Components, Parts and Interaction among them (Wagner, 2001)



Aside the thickness of the lines, an important improvement to the description can be given by the addition of a quantitative value for the interaction i.e. in a scale: *1 (min) – 10 (max)*.

The second concept relative to the *Structure*'s description is the *Isolation* that is a **reduction in** or a termination **of** integration.

The *Isolation* in some parts can be related of an intervening boundary. In other parts, *Isolation* is only the consequence of the **termination of** *Integration*.

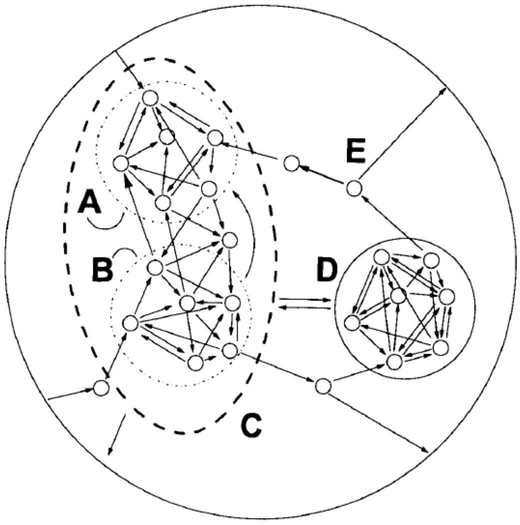
It is important to note that for this description approach *Integration* and *Insolation* are both required for *Parts*. Both *Integration* and *Isolation* can vary continuously, and therefore the extent to which a system is a *Part* – its **degree of "partness"** – is likewise a continuous variable (Wagner, 2001).

It is possible to say that the **degree of "partness"** *= function (state of the system)*

The second fundamental aspect in describing a *Structure* is the *Parts' Hierarchy*. In the approach proposed by (Wagner, 2001) the *Parts* occupying a given level in *Hierarchy* consists of **Internally Integrated** and **Externally Isolated** sets of *Components* (often, subparts) from the level below. These may also be integrated with other *Parts* at the same level in order to *Parts* at the next level. The level of hierarchy in which a *Part* occurs is purely a **function of the topology of the system** and not of the *Part's absolute size*.

The *Part's features* under study in the case of the integrated SAPPhIRE-DANE model are represented in the item of the model that actually is called *oRgan* in the SAPPhIRE model. The definition of this part is derived by the approach proposed in (Hubka & Eder, 1988).

Figure 2.15 Hierarchical relation among parts (Wagner, 2001)



The model's item *oRgan* will be the link between the *Structure's* and the *Behavior* description of the system and will contain a list of features of the *Part involved in the interaction*. A description extracted by the authors' model is the following:

oRgan: A set of properties and conditions of the system and its environment required for an interaction between them (Sartori et al., 2010)

The *Part's features* considered in the description are the ones that are **necessary and sufficient to** completely describing the *Behavior* of them that allow to the achievement of the Function and depend on the specific situation described.

2.7.2 - The Behaviour's description

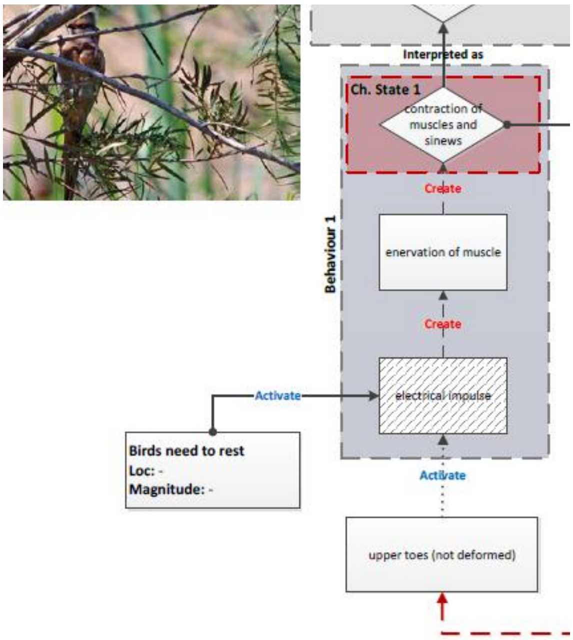
The core of the model is the behavior's description, which it is fundamental for several reasons. According to (Howard et al., 2008) the use of information about the behavior for a new design leads to an higher level of innovation respect the ones which implements the function or the structure. Moreover, the behavior's description allows understanding how the natural system "works" and how evolves in order to achieve the intended *Function*.

It is important to note that, the behavior's description has been taken from the core part of the SAPPhIRE model represented in Figure 1.24 from (Chakrabarti et al., 2005). From Chakrabarti's model, in order to properly describe the *Behavior*, have been extracted the model's items:

- Physical Effect
- Physical Phenomenon
- (change of) State

Figure 2.16 represents a detail view of the integrate SAPPhIRE-DANE models that have been used in this research as a tool for modelling the NSoI for the design tasks needed in step 4.

Figure 2.16 Behavior's description in the SAPPhIRE-DANE integrated model (Sutter, 2013)



The behavior's description starts from the lower part of the pictures. In fact, the order of the three components of the model included in the behavior 1 represented in Figure 2.16, are electrical impulse *(Physical Effect)* that create an enervation of the muscle *(Physical Phenomenon)* and finally a contraction of muscles and sinews *(change of State)*.

Two important items do the activation of the above-mentioned model's items used to describe the *Behavior* of the system:

- Input
- Part's properties

In Figure 2.16 the input is represented by the box in the lower left corner. In this case, the input is the need of the bird to rest. The information contained in the input box has been taken by the description proposed in the DANE modelling approach that allows indicating both the location and the magnitude of the input.

The other element that activates the behavior of the natural system is the *Part's Properties* box. In Figure 2.16 is represented in the lower central part. That element is a variation of the element called in SAPPhIRE *oRgan*. The Part's properties box is directly connected to the part(s) or the sub-system that is involved in the description of the specific *Behavior* under analysis.

The *Part's Properties* box is a fundamental element for the description because of that allows making a **Causal Description** of the system's *Behavior* directly ascribable to a specific part of the system that due to his *Behavior* generates a certain *Function*.

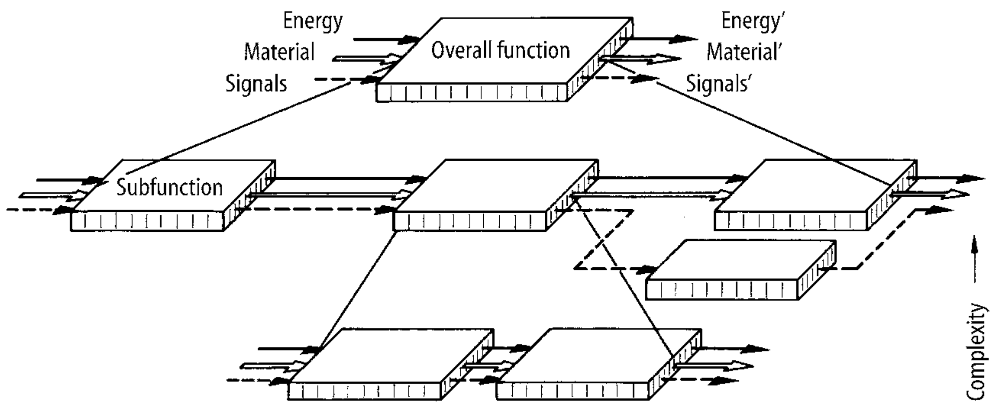
Considering now, the design phase, it is important to note that the information related to the *Physical Effect* used in Nature allows the designer to understand which is the best technology to be considered in order to implement the phenomenon in the technical system.

2.7.3 - The Function's description

In order to be the most general possible, the functional description of the system provided by the integrated SAPPhIRE-DANE model, foresee *(n)* levels of *Function* description details.

According to the view of functional modelling proposed by (Pahl et al., 2007) where the overall function can be subdivided in sub-functions as presented in Figure 2.17.

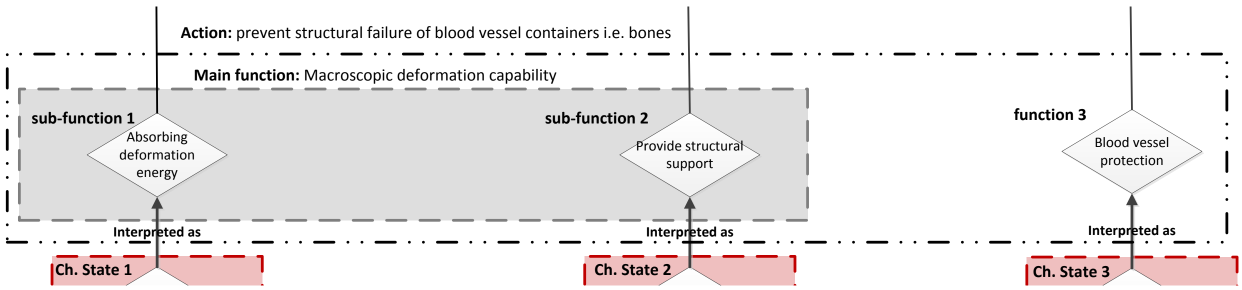
Figure 2.17 Establishing a function structure by breaking down an overall function into sub-functions (Pahl et al., 2007)



It is worth to note that each sub-function can be split in others sub-functions both at the same level of complexity or at a lower level of complexity. Furthermore, the functions can be carried on by the system either in a serial or in a parallel sequence.

As an example of modelling, consider the functional section of the SAPPhIRE-DANE model of a human bone based on the information extracted from the research of (Koester, Ager, & Ritchie, 2008) and presented in Figure 2.18.

Figure 2.18 Action, Function and Sub-Function description in the SAPPhIRE-DANE integrated model



In the excerpt of the model, it is possible to recognize three different levels of detail:

I. Action
II. Main function or Function
III. Sub-Function

In order to create a distinction between the technical systems and the Natural phenomenon it has been decide to call the overall-function with the name *Action* and its correspondent concept. The definition has been extracted from the SAPPhIRE model by (Sartori et al., 2010):

Action: *An abstract description or high-level interpretation of an interaction between the system and its environment*

It is important to note that a Natural systems has no functions to carry on, the actions performed are driven by the survival needs.

According to an interesting study about the Design architectures in Biology i.e. “the arrangement of functional elements”, there are two main design architectures: the integral and the modular ones. An integral architecture includes a complex (many-to-many) mapping from functional elements to physical components and/or coupled interfaces between components. On the other hand, a modular architecture presents one-to-one correspondence between modules and functions and specifies de-coupled interfaces between components (Pandremenos, Vasiliadis, & Chryssolouris, 2012).

The concept of Design architectures in Biology allows saying that parts, sub-systems or organs can have a specific function to carry on in order to allow the system in performing the action. This is the motivation related to the choice of using other two levels of detail for the functional description of the natural systems within the SAPPhIRE-DANE model.

Starting from each component, part or organ it is possible to follow the connection that passes through the behavior’s description reaches the correspondent *Function* or *Main-Function*. It has been necessary to subdivide the same concept in two categories in order to diversify them in two separate sub-concepts. In fact, the main-function is the combination of more than one sub-functions connected to the same number of behavior’s descriptions. On the other hand, the function is a sub-function that is connected to only one behavior. See Figure 2.17.

2.7.4 - The evolution of parameters description

The integrated SAPPhIRE-DANE model is aimed at allowing the designer a deep understanding and a precisely description the how the natural system works. In order to close the “red thread” of the description that starts from the component, passes through the behaviour, reaches the function it is important to create a correspondence with the parameters involved in the operation. In fact, the model is able to create a direct link between a specific component and the parameters that are modified by its behaviour.

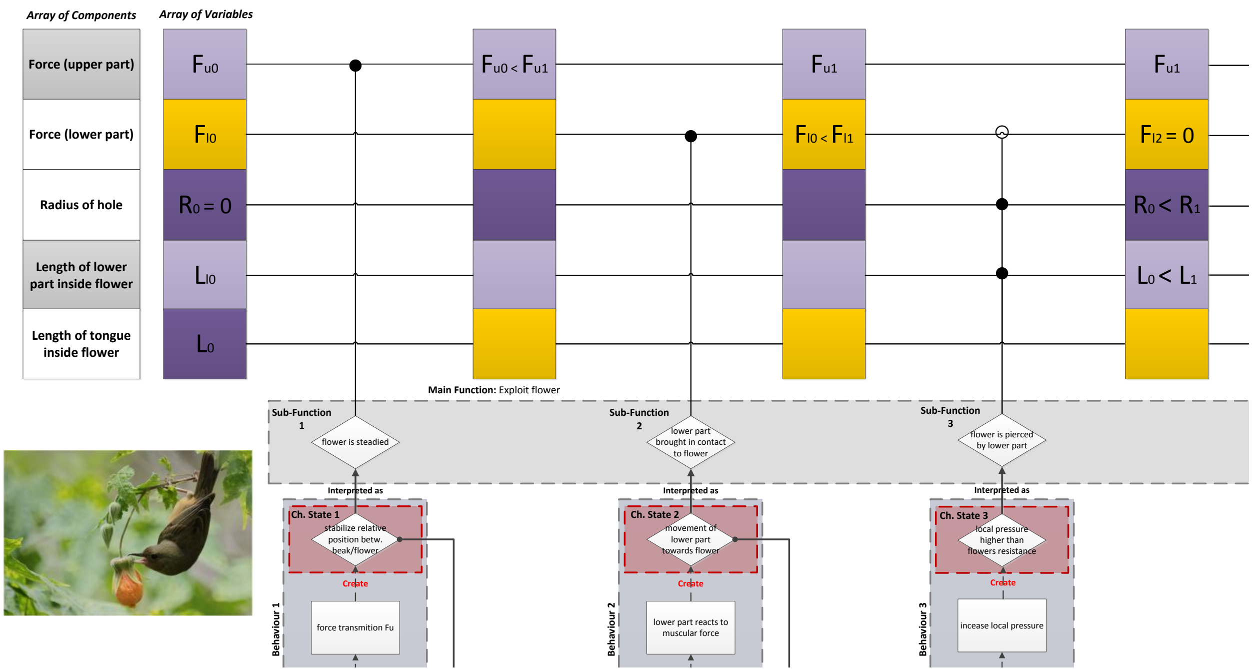
This is a completely new feature because neither SAPPhIRE nor DANE allows describing the evolution of a set of variables. The description is made using two arrays:

- Arrays of components
- Arrays of variables

In the array of components, there is a components' list that contains the items directly involved in interactions, which the designer is interested in understanding the parameters variability. It is worth to mention that in some case could be enough have a sub-list of the components. For example, composed by the ones directly involved in the interactions or the ones, that could be a good source of inspiration in the design process.

With regard to the array of components, a deepening is necessary. According to the DANE approach are considered components also things such as *Fluids* and *Forces*. In any case, in order to differentiate them they are represented differently respect to the other components (see Figure 1.25). This is the reason why in the excerpt of the model presented in Figure 2.19 the array of components includes also Forces.

Figure 2.19 Evolution parameters' description in the SAPPhIRE-DANE integrated model (Sutter, 2013)



Each component can be associated to one or more variables that are involved in the interaction. This means that one row of the *Array of Components* can correspond to more than one line in the *Array of Variables*. The *Arrays of Variables* in the model are **(n+1)** considering **(n)** the number of the *Behaviours* models. The need to have **(n+1)** *Arrays of Components* is related to the fact that in order to appreciate the variation it is necessary a modelling “station” that represent the pre and the post condition of the component.

The sub-function output and the connection lines of each row of the array of variables give a further opportunity of description. The connection between them can assume two values:

- **Full dot:** intended change/influence
- **Empty dot:** unintended change/influence

The graphical representation of the model gives the opportunity to individuate the exact location where the modification of a variable occurs and correlate it to the correspondent component or part.

In order to make the model the most flexible possible, the variables can assume the form that is more suitable for the description:

- Quantitative values
- Parameters
- Drawings or schematics representations
- Etc.

This option leads to the possibility to have a higher variety of sources of information, which increases the possibility to have more insights for the design phase.

It is worth to mention that the behaviour of the component or of the part can affect more than one variable as it is shown in the right side of Figure 2.19 with either intended or unintended changes/influences.

3 - Application of the PB-Solving methodology, Methods and Tools

This section collects and discusses the results obtained by the application of the BID Problem-Solving methodology on the selected technical problems. Moreover, it will be presented the results of the experiments where the selected tools have been applied by the designers target. The chapter is organized into seven sub-sections that can be grouped in four main categories.

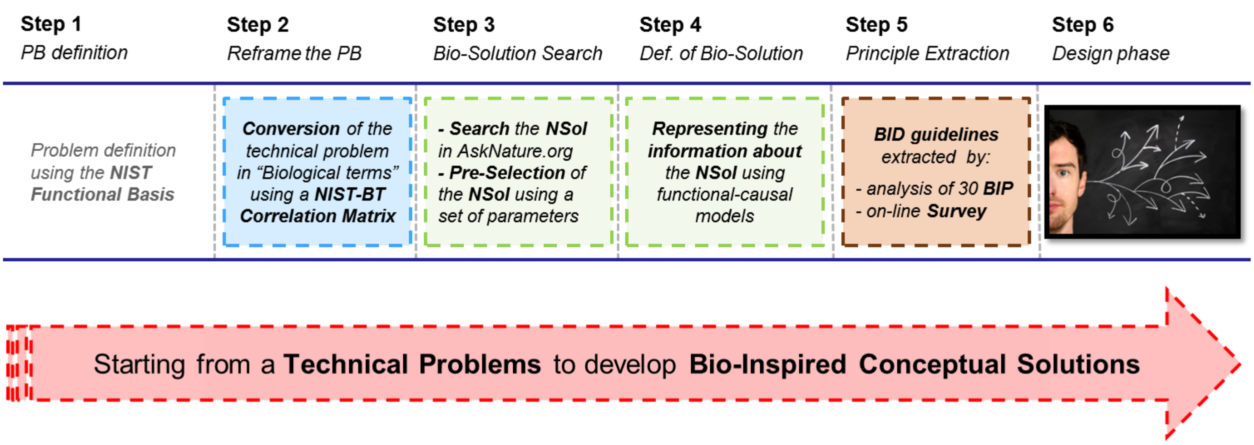
The first category is composed by two sub-sections. The former presents a schematic overview of the PB-Solving methodology and the selected tools. Then, are presented the main features of the four test cases used for the methodology's validation. The latter, concerns about the features of the experiments carried out in order to validate both the methodology and the selected tools. In this section will be presented the hypothesis, the motivations to carry on this specific validation approach, and the planning of the experiments.

The second category, which corresponds to the sub-section 3.3 -, presents the Experiment Nr. 1 that concerns with the validation of the tools use and application that have been selected in order to carry out the methodology's steps.

Afterwards, the third category that consists in three sub-sections, presents the experiments carried out in order to achieve the methodology's validations. In these sub-sections is presented the core part of the experiments, which is about the application of the methodology by three different designers on a set of four test cases.

Finally, the last section presents the Experiment Nr. 5 that has been performed on a control group in order to verify the parameters selected and used by the above-mentioned designers for the pre-selection of the NSoI.

Figure 3.1 Overview of the Six-Steps Problem-Solving Methodology and relative tools



3.1 - PB-Solving methodology validation approach and Test Cases overview

Figure 3.1 presents a schematic overview of the BID methodology proposed in this doctoral research. Furthermore, for each step is synthetically presented the tool(s) adopted.

The tools necessary to properly carrying out the steps are listed below in the same order that they appear in the methodology:

1. NIST Functional Basis
2. NIST-BT Conversion Matrix
3. AskNature.org database
4. SAPPhIRE-DANE integrated causal-functional model

These tools will be subject to the use validation by the intended designers' target. Moreover, the tools' validation allows verifying if the results obtained by the designers that use them into the validation of the methodology are consistent.

Anyhow, the aim of the methodology's validation is not on the use of tools but in the ability of the method of guiding the designer in the development of a Bio-Inspired Conceptual Solution for a technical problem. In fact, three different designers will apply the methodology individually by starting from the technical problem in order to obtain at least a conceptual solution for it. The validation of the methodology will be obtained by combining the following approaches:

A. **Ability of the methodology to guide the generation of the Bio-Inspired Conceptual Solution**
B. **Fulfilment of the project requirements by the developed Bio-Inspired Conceptual Solution**

The **Part A** of the validation has been obtained by modifying the approach proposed by (Coelho & Versos, 2010) to validate technological industrial design concepts.

The authors have proposed a set of five criterions, these validation criteria are a combination of engineering approaches with social science approaches. These criterions are mainly focused on the Industrial Design field and according to the authors' conclusions; the […] *validation process may necessitate further refinement, and improvement* […]. Some criteria regard, for example the *communication effectiveness* and the *innovation paradigm* of the BIPs that actually are outside of the scope of this research.

In order to improve the validation procedure it has been decided to separate the analysis of the Bio-Inspired Concept features from the methodology ones. In fact, this is the reason why it has been decided to separate the validation in **Part A** and **B**.

According to the doctoral research aim, in **Part A** it has been decided to focus the attention on the analysis of the methodology's features using the following set of criteria:

i. *Usability of the "Nature's Solution(s)" during the Design Phase*
ii. *Multiple requirements satisfaction approach*
iii. *Effectiveness of the methodology*

An insight into the reasons for the choice of parameters is then necessary. As emerged from the analysis of the state of the art nowadays companies are interested in using all the potentialities of the NSoI in order to improve the design of their products. Furthermore, it is important avoiding the misuse of the method. It has been show that sometimes BID is used as a simple marketing tool. This misuse individuates the NSoI a posteriori only in terms of shape and aspect in order to increase the "Natural soul" of the product. This surely increases the BIP's appeal but unfortunately waste an important opportunity in learning from Nature how to improve the design of a technical product. These are the reasons why the method should be able to easily allow the *usability of the "Nature's Solution(s)" during the Design Phase*.

An important aspect to be considered is the ability of the methodology in solving *multiple requirements*, i.e. the resolution of conflicts between non-compatible properties. This solving process can be made with compromises or with a dedicated Nature's solution.

Finally, it is fundamental that the Problem-Solving approach has to be "convergent" to a Bio-Inspired Conceptual Solution in a finite and industrially acceptable time. This aspect is checked with the *effectiveness* of the methodology.

As anticipated before, the **Part B** of the validation procedure is focused on the characteristics of the output of the methodology i.e. the Bio-Inspired Conceptual Solutions. According to the IEEE Standard Glossary of Software Engineering Terminology considering in particular the std. 610.12-1990, the validation is defined as follows:

Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled (IEEE Standards Board, 1990).

Even though, at the moment the methodology is paper based it is important to foresee a structured verification of the outputs' features.

It is worth to note that for a technical problem, the development of the requirements list according to a standard PDP gives an *objective evidence* for the validation procedure. The requirement list, made during the clarification task, allows verifying if the Bio-Inspired Conceptual Solution *fulfils the particular requirements*.

Finally, due to the fact that we are considering a Problem-Solving Methodology applied by designers it is important define what is the *intended use*. In the next sections will be defined the target of the methodology in terms of:

- Enterprises’ characteristics in terms of dimension and typology of PDP
- Designers’ capabilities in terms of:
    - Biological knowledge
    - Prior knowledge of the Problem-Solving methodology
    - Design experiences
- Products’ typology in terms of level of complexity

In order to validate both the ability of the methodology in guiding the designer in the generation of a Bio-Inspired Concept and its output’s features, the methodology has been tested on a set of four Test Cases from three designers.

Starting from technical problem, given to the designers in two different forms i.e. textual descriptions or functional models of the entire system with the correlated problems to be solved, it has been developed the requirements identification for all of them following the Task Clarification approach (Pahl et al., 2007).

The aim of the requirements identification is to generate a *Requirements List*. The requirements list´s purpose is to be used in order to control the final product concerning the aspects that were set up at the beginning of product development (Pahl et al., 2007). The basis of the requirements list was a questionnaire, which was answered by experts about the systems. The questionnaire mainly answered the three following questions.

1. *What are the objectives that the intended solution is expected to fulfil?*
2. *What properties must it have?*
3. *What properties must it not have?*

Moreover the geometries and the configurations of the systems were given.

After this first stage of the Task Clarification there has been the search for further requirements that has started from the basis of the given customer questionnaire. In fact, more customer requirements were developed. In order to identify and structure these, three categories were set up. According to (Pahl et al., 2007) these are:

a. Basic requirements,
b. Technical performance requirements
c. Attractiveness requirements

Basic requirements are implicit which means that they are not stated directly by the customer. Nevertheless, they are considered as apparent and naturally. These requirements must be investigated by the company itself and may be determined by departments like sales or product management.

Technical performance requirements are explicitly expressed by the user and are thus more concrete than basic requirements. Hence, the customer delivers their values as well as their importance.

Attractiveness requirements are implicit ones of which customers are normally not conscious. Their purpose is to differ from competitors.

Afterwards, these three categories were filled by considering the given questionnaire and by further analysis with the project's leaders. This structure helped not to forget important aspects and to think in different classes.

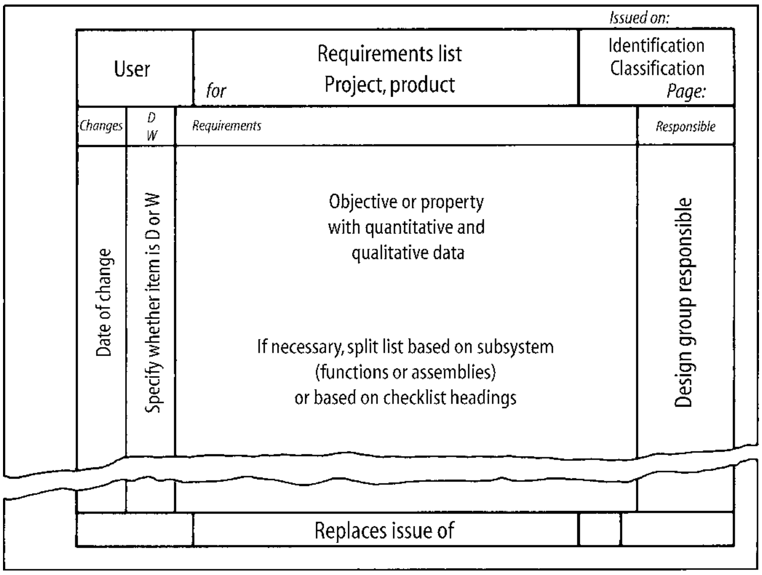
After having identified and structured the customer requirements, they needed to be detailed and expanded. Therefore a checklist was used which provided certain classes to structure the requirements at hand and to fill white gaps which have not been clarified yet. Table 3.1 presents the checklist proposed by (Pahl et al., 2007).

Table 3.1 **Checklist for setting up a requirements list** (Pahl et al., 2007)

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of despatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

By allocating the customer requirements from the steps above to these classes and by defining requirements for terms, which have not been thought about, yet, the requirements lists were compiled. The format adopted in this research is the one proposed by (Pahl et al., 2007) and schematically presented in Figure 3.2

Figure 3.2 Layout of the Requirement List (Pahl et al., 2007)



With the aim of providing a quick overview on the test cases used for the methodology's validation, these are listed briefly hereafter.

The first two test cases come from the field of the underwater pumping systems. Due to the fact the systems are placed in the farmland sometimes the rats eat the rope that make these systems falling to the bottom of the well. The underwater pumping systems in Sardinia, where there is a serious lack of water for the irrigation, can reach deeps of 250 [mt].

Table 3.2 Test Case A – Clamp mechanism for underwater Pumping Systems rescue

Test Case A	Problem Description
	**Clamp mechanism for underwater Pumping Systems rescue** - *Capacity to grab the upper part of the Pumping Systems* - *Capacity to develop a sufficient clamping force to sustain the weight of the PS*

In order to avoid the loss of the well due to the obstruction caused by the presence of the fall pumping system on the bottom is necessary to develop a system for its rescue. The presence of a check valve at the output of the pumping system, which causes that the long water pipe, is full of water along with the power cables and control and the supporting rope makes the pumping system very heavy. These are the main reasons for the requests to the system presented in Table 3.2

The fall of the underwater pumping system inside the well generates a further problem related to the different longitudinal stiffness of the pipe, the wires and the electric cables. This problem leads to the second Test Case presented in Table 3.3

In fact, in the practice it is necessary developing a certain rigidity of the system composed by the rope, the water tube, and the cables. This can be obtained using cable ties that bind together the different “wires”. Several problems related to the use of standard plastic ties make that is necessary to develop a new solution to ensure a correct binding of the “wires” that also allows rescuing the fall pumping system.

Table 3.3 Test Case B – Tie mechanism for underwater Pumping Systems

Test Case B	Problem Description
	**Tie mechanism for underwater Pumping Systems** - *Capacity to fasten/tie the electrical wire, the rope and the water tube* - *Capacity to develop a sufficient clamping force to ensure the binding*

The above-mentioned problems are the reasons why the second *Test Case* is about the development of a specific Bio-Inspired conceptual solution for the tie mechanisms.

The third *Test Case* is about the development of a non-standard solution for the bicycles luggage rack used for a bike sharing system.

Table 3.4 Test Case C – Luggage rack for bicycles of a bike sharing system

Test Case C	Problem Description
	**Luggage rack for bicycles of a bike sharing system** - *Capacity to fasten different kinds of bags/luggage* - *Capacity to transport more than one bag/luggage*

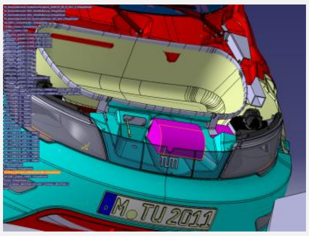
The properties of the systems presented in Table 3.4 are necessary because the users of the bicycle are always different. In fact it is not possible foresee the typology of bags of each user and it is necessary a luggage rack suitable for baggage of different kinds.

The bike-sharing system project called PSSycle – is a prototype of a mobility concept based on an electrical bike – is one of the demonstrators of the SFB 768 i.e. **S**onder**f**orschungs**b**ereiche that in English means CRC, Collaborative Research Centres founded by the DFG - **D**eutsche **F**orschungs**g**emeinschaft (German Research Council).

The last test case, which is part of the project called visio.m (http://www.visiom-automobile.de) that deals with the development of a new electric concept car and has been financed by the **B**undes**m**inisteriums für **B**ildung und **F**orschung – BMBF i.e. Federal Ministry of Education and Research of Germany.

Due to the number of design tasks present in the project, for the methodology's validation it has been assigned to solve a single sub-problem regarding the cable winder.

Table 3.5 Test Case D – Retracting Cable Mechanism for electric cars

Test Case D	Problem Description
	Retracting Cable Mechanism for electric cars
	- *Capacity to connect the electrical vehicle to a standard socket* - *Capacity to collect the cable on board of the car (cable winder)*

In fact, the last *Test Case* is about the development of a non-standard Bio-Inspired Conceptual Solution for the problem for a system to collect and retract the electrical cable of an electric vehicle (Table 3.5).

3.2 - Designers and Experiments' features

The five experiments conducted for the validation procedure can be subdivided in two categories according to those who took part:

- Control groups
- Single Designers

In the following tables, it will be schematically presented the main features of the participants to the experiments in terms of number, experience, nationality, and age.

Table 3.6 Designers' features for the Experiments Nr. 1 and Nr. 5 – Tools' Validation

	Experiment #1	Experiment #5
Participants:	19 Designers – Mechanical Engineers	7 Designers – Mechanical Engineers
Experience:	2°/3° Design Experience	2°/3° Design Experience
Nationality:	Italian	Italian
Age:	25 < age < 30	25 < age < 30

The designers that constitute the *Control Groups* are students in their final semester of the last year of the Master Degree of the Faculty of Mechanical Engineering at the Politecnico di Milano. The students were taking part in the course: **Methods & Tools for Systematic Innovation** given by Prof. Gaetano Cascini during the academic year 2012 – 2013.

The adoption of the control groups is linked to the need to validate the use of the selected instruments to perform the steps of the methodology of Problem-Solving. At the designers has been asked to carry on a specific tasks i.e. the problem definition, the application of the correlation matrix etc. using the correspondent tool.

Three different designers to which have been asked to apply the entire methodology have carried out the second set of experiments. Table 3.7 presents the features of the designers that have applied the Problem-Solving Methodology to a set of four *Test Cases* as introduced in the previous section.

Table 3.7 Designers' features for the Experiments Nr. 1, 2 and 3 – Methodology's Validation

	Experiment #2	Experiment #3	Experiment #4
Participants:	Designer #1	Designer #2	Designer # 3 [*]
Experience:	1° Design Experience (Semester Thesis)	1° Design Experience (Semesterarbeit)	6 Concepts Developed 2 Concepts Realized (2007 – 2013)
Nationality:	Australian	German	Italian
Age:	≤ 25	≤ 25	>30

The task asked to the designers has been the following:

Starting from a given technical problem apply the methodology in order to conceive a new Bio-Inspired Conceptual Solution.

A clarification about the Designer Nr. 3, which is the researcher that developed the methodology, is therefore needed. According to the lectures of Prof. Amaresh Chakrabarti on the Design Research Methodology (Blessing & Chakrabarti, 2009), during the application of the methodology by the Researcher it is possible to consider that:

- **The Researcher is acting as a User/Designer [*]**.

The author has attended the lectures during his visiting period at the Lehrstuhl für Produktentwicklung (Institute of Product Development) at the TUM – Technische Universität München. During the research exchange, the author took the course about DRM given to the researchers of the institute in the Summer Semester 2013.

3.2.1 - Hypothesis, Motivations and Methodology's Target

In order to proceed with the Methodology's validation some assumptions have to be introduced.

The first hypothesis is related to the designers' knowledge. Because it is not possible to test every level of design experience and knowledge of the method, it has been decided to apply the methodology on these two classes of the population:

Lower limit

- Designers with NO design experience
- Designers with NO knowledge about the Problem-Solving Methodology

Upper limit

- Designer with 5-6 design experiences
- Designer with full knowledge of the Problem-Solving Methodology

This hypothesis is usually adopted in social sciences in order to validate theories about human behaviours. Due to the fact that is not possible to consider each person, the population is subdivided in homogenous classes, and then extreme sides of the population are studied and tested.

On the ambit of this research, this assumption allows validating the Problem-Solving methodology use for the central population in respect to the above-mentioned classes of designers.

The second hypothesis that has to be introduced is about the use of the method by the designer, which developed the Problem-Solving Methodology.

- ❖ **The researcher is acting as a user/designer itself**

Due to this last hypothesis, it has been decided to ask to the Designer Nr. 3 to solve a set of two technical problems.

In order to identify the typology of the products to which the methodology can be applied it is fundamental to individuate a characteristic to take into consideration in order to classify them.

(Hubka & Eder, 1988) have proposed a classification attempt based on the Level of complexity in their book Theory of Technical Systems. See the details in Table 3.8

Therefore, a further hypothesis on the typology of products developable with the methodology is necessary:

- ❖ **The methodology will be tested on problems pertaining to products within a defined range of complexity i.e. from *Level I* to *Level III***

The range of complexity chose is correspondent to the range of complexity individuated during the BIPs' analysis presented in section 2.6.1 -

Table 3.8 Levels of Complexity proposed in Theory of Technical Systems by (Hubka & Eder, 1988)

Level of complexity	Characteristics	Examples
Level I - Part, Component	Elementary system produced without assembly operations	*Bolt, bearing sleeve, spring, washer*
Level II - Group, Mechanism, Sub-Assembly	Simple system that can fulfill some higher functions	*Gear box, hydraulic drive, spindle head, brake unit, shaft coupling*
Level III - Machine, Apparatus, Device	System that consists of sub-assemblies and parts that perform a closed function	*Lathe, motor vehicle, electric motor*
Level IV - Plant, Equipment, Complex Machine Unit	Complicated system that fulfills a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity	*Hardening plant, machining transfer line, factory equipment*

The last aspect to be taken into consideration is the industrial application of the BID approach. From the analysis of the state of the art, it has been deduced that only big enterprises have enough resources to follow a completely new Design approach such the one required for the use of Nature as a Source of Inspiration. In order to overcome this limitation, it has been chose to use and adopt only free available tools. These allow developing a Problem-Solving Methodology that can be chosen also by Small-Medium Enterprises that have limited resources.

Summarizing the hypothesis and the consideration made so far it is possible to individuate clearly the target of the methodology that has been schematically presented in Table 3.9

Table 3.9 Methodology's Target

Target	Description	Features
Designers:	Limited Design Experience	*2nd – 3rd Design Project or 1.5/2 years of Design Experience*
	No Biological knowledge	*Industrial Designers or Engineers*
Products:	Technical systems	*Level of Complexity from I to III*
Enterprises:	Small-Medium	*Interested in using Nature's Best ideas to solve technical problems*
	Product Development Process	*Not centralized*

3.2.2 - Experiments' Planning

As discussed already in the previous section the aims of the validation approach are:

i. Demonstrate the capability of the method in guiding the designer in the generation of the Bio-Inspired Conceptual Solution
ii. Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled

These two aspects can be validated through the development of a set of Test Cases by applying the entire Methodology. Anyhow, also if the validation is methodology centred, it is necessary planning a set of experiment regarding the use of the tools for the design activities.

In order to validate the tools used by the designers during the Methodology's Validation a set of experiments have been carried out in order to answer to the following questions:

1. *Why is necessary browsing the AskNature database by categories?*
2. *Is the problem description in NIST terms robust?*
3. *Is the problem description in BT terms robust?*
4. *Are the parameters chosen for the NSoI Pre-Selection robust?*

The validation planning comprises three clusters of experiments. In the first cluster are included the experiments aimed at validating the hypothesis about the use of the database AskNature.org and the use of the tools for the problem modelling. Then the core part of the validation that comprises three experiments that provide the application of the methodology in a set of four test cases. Finally, in the last cluster a control group will validate the parameters chosen by the designers for the pre-selection of the NSoI.

3.2.2.1 AskNature.org use and Tools' Validation

A group of designer that are the designer target has carried out this first set of experiments on the Experiment Nr. 1.

These experiments have been structured as follows:

- Introductory presentation of the overall Problem-Solving Methodology (c.a. 15 minutes)
- Presentation about the experiment's tasks with a practical example (c.a. 15 minutes)
- Length of the experiment 2 hours

Output: Creation of a report of the results by using a standard report file

It is important to note that for the designers involved in the experiment it was the first time they learn about the Problem-Solving Methodology. Furthermore, it has been asked to work independently.

3.2.2.2 Methodology's Validation

In order to perform the methodology's validation it has been asked to three designers to apply the methodology from Step 0 i.e. the Requirements Identification, to the step 6 i.e. the Design Phase. In fact, in the last step the designers have to develop the Bio-Inspired Conceptual Solution for the correspondent technical problem.

The core of the methodology's validation can be split in two parts. The Designers belonging to the lower limit have performed the first part, which consists of two experiments i.e. Experiment Nr. 2 and Nr. 3. On the other hand, the second part is composed by a single experiment i.e. Experiment Nr. 4 that has been carried out by the designer belonging to the upper limit but foresee the development of two Bio-Inspired Conceptual Solutions.

The former set of experiments has been structured has follows:

- Introductory presentation of the overall method (c.a. 1 hour)
- Instruction sheet with the tools and the necessary scientific references
    - Methodology's framework
    - Name and references of the tools for each step
    - Timeline

The designers have been supervised with a weekly review of the work done. It is important to note that there has been any interference in the proposed work. The aim was checking the evolution of the work and the designer's behavior in terms of understanding of the methodology and limits of its application.

It is worth to note that, the designers have carried out the experiments as a side activity between the others tasks such as classes, sport etc.

- Total length of the experiment 4 months

As output of the experiments has been developed a semester thesis-work that contains the following information:

- Step by step description of the methodology's application
- Description and drawings of the Bio-Inspired Conceptual Solution
- Questionnaire about the tools use and the methodology application

The latter experiment i.e. experiment Nr. 4 has been carried out by the Designer Nr. 3 as a side activity respect the research collaborations and the doctoral tasks such classes, examination support etc., lasting a total of 2 months.

Output: Description and drawings of the two Bio-Inspired Conceptual Solutions

It is important to note that the requirements identification has been supervised by the responsible for the projects. Furthermore, they have performed a verification of the effectiveness of the proposed Bio-Inspired Conceptual Solutions.

3.2.2.3 Parameters' for the pre-selection of the NSoI Validation

Finally, the last experiment i.e. Experiment Nr. 5, has involved a control group in order to validate the consistency of the parameters used by the designers for the pre-selection of the NSoI.

This experiment has been structured as follows:

- Introductory presentation of the overall Problem-Solving Methodology (c.a. 15 minutes)
- Presentation about the experiment's tasks with a practical example (c.a. 15 minutes)
- Length of the experiment 2 hours

Output: Creation of a report of the results by using a standard report file

It is worth to note that this last experiment has been performed with the same designers that have carried out Experiment Nr. 1 Moreover, also if the designers are the same ones their level of knowledge about the method and the tools has changed in between the experiments. In fact, at the moment of the Experiment Nr. 5 they have already received:

- Introductory presentation of the overall Problem-Solving Methodology (c.a. 15 minutes)
- Presentation about the experiment's tasks with a practical example (c.a. 15 minutes)
- Feedbacks about the results of Experiment Nr. 1

At this point the designers were familiar with the overall Problem-Solving Methodology and the relative tools but not with the parameters for the pre-selection of the NSoI.

3.3 - Experiment Nr. 1

The aim of this set of experiments is the validation of the following aspects:

- The search by keywords by designers without Biological Knowledge in AskNature.org
- The problem description by using the NIST Functional Basis
- The use of the correlation matrix NIST-BT

The details about the participants to the experiment have been presented in Table 3.6 During the experiments it has been asked to the designers to work on a single problem that corresponds to the test case presented in Table 3.4 and solved by Designer Nr. 3

The description of the problem given to the participants is the following:

❖ *For a new bike-sharing system, it is necessary developing a device to fasten different kinds of bags/luggage.*

3.3.1 - The Tasks

Starting from the above-mentioned description of the technical problem it has been asked to the participants to carry on three different tasks that will be described singularly in the following sections.

3.3.1.1 Free search in AskNature.org

Biologists with solid backgrounds in disparate fields of biology have created the database of natural phenomena that is continuously updated with new phenomena that are classified into biological functional categories.

The database can be use from everyone, also people with no biological knowledge like the designers. It is fundamental understanding, which are the problems in the use of the database.

The following questions have to be verified:

- Is the DB usable by designers with no biological knowledge?
- Do the designers have to pay attention to some aspects in the use of the database?
- Which is the best way to use the database for the designers?

In order to achieve this goal it has been asked to the participants to use freely the database by generating a set of keywords in order to individuate the most suitable NSoI to solve the given technical problem.

3.3.1.2 The description of the Technical Problem in NIST terms

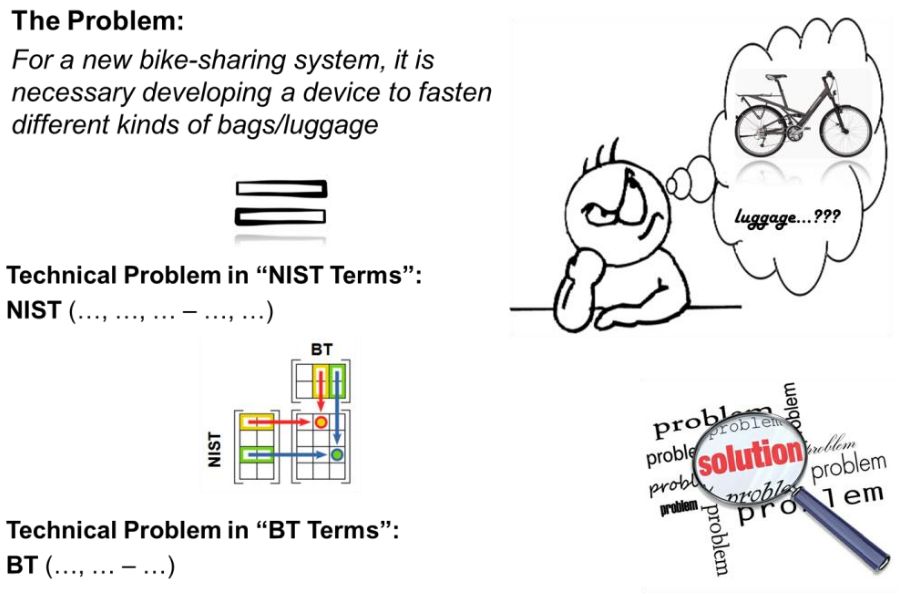
Due to the fact, the NIST is a tool that is adopted into the methodology without being modified it is important to verify its use by the intended target of designers. It is obviously out of the scope of this research verifies the ability of the NIST-FB in describing the problems but it is fundamental verify the following question:

- Is the problem description in NIST terms robust?

It is worth to note that an adequate description of the problem using the NIST-FB is fundamental because it will be used as an input for the BT-NIST correlation matrix.

To designers has been then asked to realize the NIST description of the given problem.

Figure 3.3 Overview of the translation process of a Technical Problem into Biological Terms



3.3.1.3 The use of the BT-NIST correlation matrix

In order to correctly translating the technical problem in ***biological terms*** by using the correlation matrix it is fundamental verify its use for a given input i.e. the technical problem expressed in ***NIST terms***.

The question to be answer is the following:

- Is the correlation matrix robust in the translation of a given problem in biological terms?

The last task asked to the designers has been to apply the correlation matrix using the technical problem described in NIST terms as an input.

3.3.2 - The Results

The results will be presented hereafter following the same sequence used in the previous section where the tasks have been presented.

3.3.2.1 Free search in AskNature.org

In order to better understanding the typology of keywords used for the free search into the database it has been necessary to elaborate them into clusters.

First of all the keywords have been classified according to the problem solving process if they are a:

- Problem description
- Solution

Then it has been verify if they have been used as:

- Name
- Verb
- Adjective

Finally, it has been verify if they are:

- Functions
- Properties
- Others

In Table 3.10, all the results of the classification are presented.

Table 3.10 Keywords used in the free search of the AskNature.org database

Keywords	Count	Problem-Solving process		Legend
		Problem Description	*Solution Implementation*	
Adhesion	1	n		Function
Adhesive	1		n/adj	Property
Block	1	n/v		Others
Carry	1	v		
Fasteners	1		n	
Fix	1	v		
Grocery	1			
Immobilize	1	v		
Keep	1	v		
Lock	1	v		
Move	1	v		
Pull	1	v		
Rack	1		n	
Recycle	1			
Sharing	1			
Shopping	1			
Smooth	1	adj		
Surface	1	n		**Percentage**
Trash	1			1,3%
Fast(en)	2	v		2,5%
Object(s)	2	n		2,5%
Plastic	2			2,5%
Transport/Transportation	2	v		2,5%
Weight	2	n		2,5%
Attach	3	v		3,8%
Hold	5	v		6,3%
Luggage	5		n	6,3%
Fasten	8	v		10,0%
Bike/Bicycle	14			17,5%
Bag(s)	16		n	20,0%

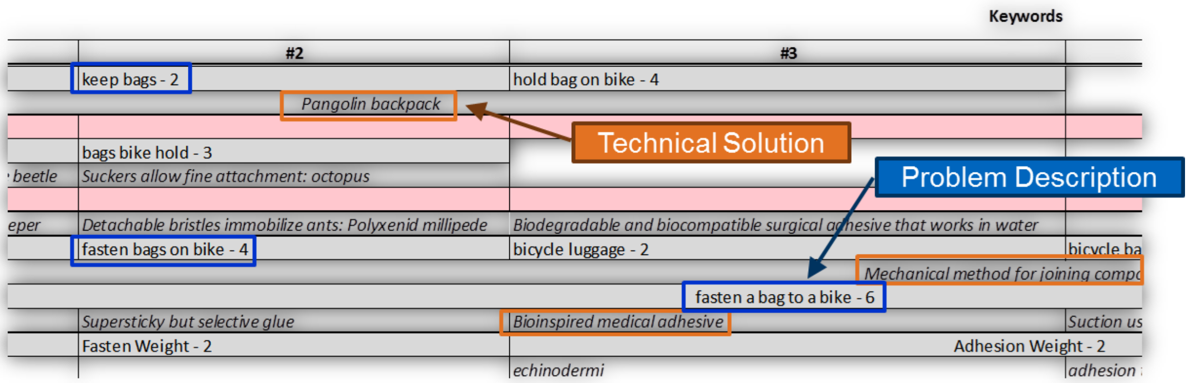
Aside to the keywords' analysis it has been performed an analysis on the typology of sentences used by the designers for the search into the database of Natural phenomena.

The studied parameters are the following:

- Length of the search sentence i.e. number of words
- Typology of sentence

As an example, an excerpt of the sentences used for the search is presented in Table 3.11

Table 3.11 Examples of search sentences used for the search



The results of the analysis of the length of the sentences in terms of number of words is presented in Table 3.12

Table 3.12 Keywords used in the free search of the AskNature.org database

Number of words	Count	Percentage
6	3	8%
5	1	3%
4	5	14%
3	4	11%
2	13	36%
1	10	28%

Table 3.13 Experiment Nr. 1 – The functional classes used to describe technical problems in NIST terms

Class *(primary)*	Secondary	Tertiary	Count	Percentage
Connect	Couple	Join	8	40%
Connect	Couple	Link	5	25%
Connect	Couple	Join/Link	7	35%

3.3.2.2 The description of the Technical Problem in NIST terms

Starting from the technical problems given by a textual description, the designers have applied the NIST functional basis in order to find the correct functional description to the problem. The results of the problem in NIST terms are presented in Table 3.13

As introduce in section 2.2.1 -the description of a technical problem using the NIST functional basis is the following:

Function = Action + Flow

In Table 3.14 are presented the flows used to describe the technical problem in NIST terms.

Table 3.14 Experiment Nr. 1 – The flows used to describe the technical problems in NIST terms

Class *(primary)*	Secondary	Tertiary	Count	Percentage
Material	Solid		1	8%
Material	Solid	Object	12	92%

Finally, Table 3.15 presents the result about the typology of description used by the designers.

Table 3.15 Experiment Nr. 1 – The typology of the description of the technical problems in NIST terms

Typology of NIST description	Count	Percentage
Action	7	35%
Action + Flow	13	65%

In fact, some designers use only the action verb to describe the technical problem while others use both the *Action* verb and the *Flow*. It is important to note that it is not possible describe the function using only the *Flow*.

Table 3.16 Experiment Nr. 1 – The technical problems in Biological terms due to the application of the BT-NIST correlation matrix

Group	Sub-Group	*(Natural)* Function	Count	Percentage
Make	Physically Assemble	Structure	15	45%
Move or Stay Put	Attach	Temporarily	14	42%
Move or Stay Put	Attach	Permanently	3	9%
Make	Chemical Assemble	Attach	1	3%

3.3.2.3 The use of the BT-NIST correlation matrix

The designers have used the NIST description of the technical problem obtained in the previous experiment as an input for the BT-NIST correlation matrix. Table 3.16 presents the results about the use of the correlation matrix in order to obtain the description of the technical problem in *Biological terms*.

3.3.3 - The Findings

Due to the need of validating the entire Problem-Solving methodology and not the single tools' use, it is worth to draw some conclusions separately respect to the methodology's validation procedure. Also in this section, you will use the same presentation order used in the previous sections.

3.3.3.1 Free search in AskNature.org

Analysing the keywords used for the search it is possible to conclude that the designers without Biological Knowledge in a free search in a database of Natural Sources of Inspiration:

- Use " technical" keywords
- Use keywords related to the characteristics of the specific solution for the technical problem
- Do not use words related to Natural phenomena

Another important aspect emerged by the experiments is related to the type of queries used for the search. The results show that:

- The number of words used in the queries are on average too high

Considering the examples in Table 3.11 it is possible to draw some partial conclusions on the use of the database of Natural phenomena and it is possible to derive some considerations on the identified sources of inspiration.

The use of "technical" keywords lead to the identification of BIPs i.e. Bio-Inspired adhesive tape, Pangolin backpack etc. that have been already developed by other companies. These BIPs are stored in the DB as examples to provide some idea of possible application of the NSoI but cannot represent the result of the search for the NSoI as solutions for new technical problems.

The experiment shows that the approach in the use of the database by designers is limitative.

The use of keywords for the search for the NSoI creates, for a given technical problem, a bigger variety in the NSoI obtained that is function of the selected keyword. Moreover, the results belong to a bigger number of different functional classes that make more difficult to have an acceptable level of repeatability of the results.

Finally, it is possible to conclude that due to the keywords search strategy by designers without Biological knowledge the database of Natural phenomena is used such a database of "technical solutions". It is therefore necessary to identify a strategy to use the database most adequate.

3.3.3.2 The description of the Technical Problem in NIST terms

It is important to underline that is out of the scope of the thesis make any kind of validation about the ability of the NIST Functional Basis in describing technical problems properly. The aim of the experiment has been demonstrating the repeatability of the use of the NIST Functional Basis by the designers, which represent the target for the use of the methodology.

The totalities of the designers have identified one or both classes of the NIST functional basis useful for the description of the given technical problem.

The 25% of the designers chose to use only the class Connect – Couple – Link which is not completely appropriate for a system that has to allow a removable assemble of the luggage/bags.

Table 3.17 confirm the consideration analysing the correspondent words to the NIST-FB classes.

Table 3.17 Excerpt of the NIST basis reconciled function set (Hirtz et al., 2002a)

Class *(primary)*	Secondary	Tertiary	Correspondents
Connect			*Associate, Connect*
	Couple	Join	*Assemble, Fasten*
		Link	*Attach*

This indicates that in order to properly using the NIST-FB the designers have to pay attention in the classes they choose in order to properly describing the technical problem.

3.3.3.3 The use of the BT-NIST correlation matrix

The results of the experiment about the use of the correlation matrix show that there are not big problems in the use of this tool by the designers. In fact, the 91% of the designers have individuated the correct class of natural functions of the Biomimicry Taxonomy.

Only the 9% have obtained a translation of the problem in Biological terms that is not coherent with the given problem. The class of Natural function individuated is Move or Stay Put – Attach – Permanently.

3.4 - Experiment Nr. 2

Designer Nr. 1 (See Table 3.7 for the details) has applied the problem solving methodology on a clamp mechanism for underwater pumping systems rescue. The problem has been presented as test case in Table 3.2

Motivation: No standard system exists for the retrieval of the underground water pumping system. Through application of the Bio-Inspired Design, one shall be designed, whilst also investigating the effectiveness of the Problem-Solving Methodology utilized for the concept.

Goals: Develop a Bio-Inspired *Conceptual* Solution for the retrieval of the underwater pumping systems through the implementation of Nature's solutions.

In order to achieve this goal to the designer has been asked to apply the methodology by following a set of tasks:

- Develop a requirement list following the (Pahl et al., 2007) approach
- Apply the entire methodology following a time-line and using the set of tools provided
- Develop a Bio-Inspired Conceptual Solution that fulfil the requirement list
- Write a report on the entire process
- Write a report on the conceptual solution
- Compile a questionnaire about the method

The final results have been presented in (Boyle, 2013).

3.4.1 - Case Test A – The Technical Problem

In order to obtain a standard starting point to all the experiments according to (Pahl et al., 2007) it has been asked to the experts/customers to fulfil a standard questionnaire about the problem. In fact, the questionnaire with the answers of the experts has been given to the designer as a base to develop the requirements identification.

Questionnaire

1. **What are the objectives that the intended solution is expected to satisfy?**

    ✓ *Ability to grab the upper part of the pumping systems e.g. electrical wire, rope the water tube*
    ✓ *Ability to develop a sufficient clamping force to hold the weight of the pumping system*

2. **What properties must it have?**

    - *Ability to resist to water*
    - *Ability to block even larger objects as rope nodes and probes*
    - *Ability to fit into the hole in the ground*
    - *Ability to "self-grab" (or due to a signal/input) the upper part of the pumping system*
    - *Possibility of mounting without tools*

3. What properties must it not have?

- *Complexity*
- *Difficult installation*

Figure 3.4 Side view and top view of the well with the underwater pumping system installed

Furthermore, the specification about the dimensions of the components and some pictures has been given to the designer.

Figure 3.5 Winch to drop the underwater pumping system into the well

3.4.2 - The Problem Solving Process

Starting to the questionnaire, the pictures of the system and some meeting with the expert the requirements list has been developed and it is provided in the (Appendix A).

The outputs of each step that have been extracted from (Boyle, 2013) are reported in the following sub-sections.

3.4.2.1 Step 1: The Problem Definition

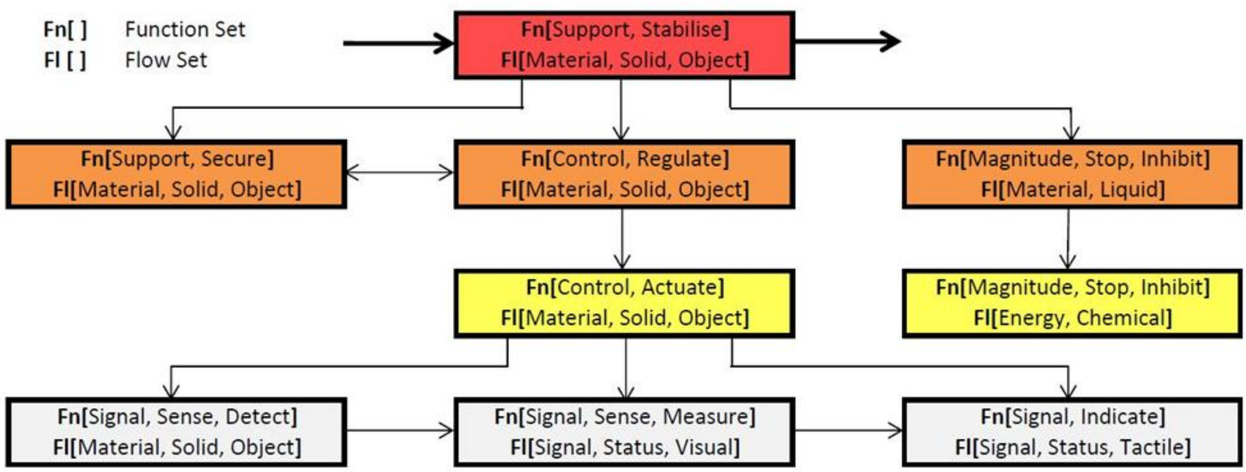
Starting from the requirements list the designer defined a function schema that describes the technical problem and the correlated sub-problems.

[…] The levels of the hierarchy in Figure 3.6 represent the decomposition of the critical function of the technical problem into supporting functions and sub-functions. That is, a tier may be viewed as a facet or component of the one above. As such, the NIST definition “Signal, Detect – Material, Solid, Object” can be seen to facilitate the higher level function “Control, Actuate – Material, Solid, Object”. In turn this block ‘feeds’ the functionality of its higher-level counterpart, as denoted by the arrow. The hierarchy has been divided into the respective actions to which each element of the problem definition set relates. For instance, moving from the left most blocks in Figure 3.6:

- Function group one – Action of structural stability upon material flow
- Kinematik Action upon material flow
- Prevention of actions from disrupting the mechanism’s operation.

Members of the NIST set, once separated as described, were analyzed for their dependence upon one another and in doing so the division between the hierarchical levels was established. This was a manner by which logical categorization and ensuing precedence of functions and sub-functions beneath the overall system was able to be implemented. […]

Figure 3.6 The technical problem in NIST terms set defined as a hierarchical structure



[…] The motivation behind establishing the echelons within the NIST function set in accordance with the structure of (Pahl et al., 2007) was the determination of the preeminent action which enables the overall system to achieve its required objectives. This would then be subsequently supports by the remaining elements in a series of co-dependent interactions. It may be observed from Figure 3.6 that the critical function was:

Support, Stabilize – Material, Solid, Object

This aspect of the general problem description was evaluated to possess the greatest bearing upon the ultimate design and operation intentions of the conceptual solution. The mechanism, as per the client's Pumping System Retrieval Requirements Identifications document has a core, simple, functional objective; it must be capable of *grabbing* and *holding* the pumping system during the rescue proves. This is the very base functionality as identified by the client and therefore it follows the base or 'overall' function must embody this. Deconstruction of the objective yields two distinct, separate actions – that of 'grabbing' and that of 'holding'. Examining the NIST problem set it is clear the elements within the Control and Support group are most relevant in achieving these aims, and thus the following list of eligible functions is obtained:

- Control, Actuate – Material, solid, object
- Control, Regulate – Material, solid, object
- Support, Stabilise – Material, solid, object
- Support, Secure – Material, solid, object

While the remaining definitions *contribute* to the mechanism's functionality they do not directly *enable* said functionality as the above members do. As the motivation for the hierarchical structure was to identify the main *objective* function of the system, they may be excluded from the selection set. Following in this vein, the two processes above must be categorized into primary and secondary actions based upon their relationship with each other – that is, the interaction between the grabbing and the holding of the pump and pipeline, the order in which they occur and the implications of the absence of one or the other will indicate which is the prominent function. In its most abstract form the solution is to be applied in a pumping system *rescue* capacity. It is paramount, as such that the mechanism is possessed of the structural integrity to support the weight of this system. Without the necessary strength to hold it during period of ascent or descent the conceptual design will be incapable of complying with the client's requirements. Furthermore, even should the mechanism be able to affix itself securely to the pipeline, if it is too weak to stabilize and support the system it again fails to meet the intended objectives. Considering this, it may be said that in order to *hold* the system, the mechanism must have the capability to *grab* it. Conversely, however, the design's ability to *grab* is not indicative of its ability to *hold*. In symbolic logic, this may be represented by "*Holding* = *Grabbing".* This states that the holding ability *necessarily entails* the grabbing ability, but does not guarantee the reverse. That is, the grabbing ability does *not necessarily entail* the holding ability. Therefore, it may be seen that the latter action *supports* the former in a physical sense and is as such regarded as a component function. The grabbing is represented from a NIST perspective in the Control elements within the problem set, and the holding by the Support group. This reduces the selection set to the following functions:

- Support, Stabilise – Material, solid, object
- Support, Secure – Material, solid, object

The NIST definition of secure is “to firmly fix a flow path”, and the correspondent terms are “constrain, place, fix” (Hirtz, Stone, Mcadams, Szykman, & Wood, 2002b). It, in essence, describes the function of holding a flow with fixed orientation or position. Stabilize is duly defined as “to prevent a flow from changing course or location”, with correspondents “steady”. In the context of the pumping system rescue mechanism, this relates to the action of supporting the weight and preventing slip throughout the retrieval procedure. It may be said, then, the ability to stabilize is a more critical factor in the mechanism’s operation than that of securing a fixed orientated. This is because the latter does not directly correspond to the client’s requirements of *holding* the weight of the system, whereas the former is a necessity for achieving this objective. The overall function selected from the NIST set of problem definitions for the conceptual solution for the purpose of complying with the objectives of the mechanism as an entity is thus **Support, Stabilize – Material, Object, Solid**.

Progressing further down the echelons the second tier represents functions, which contribute directly to the overall function identified above. Controlling the actuation, maintaining structural integrity through inhibiting the penetration of water and holding the orientation of the pipe fixed to reduce system disturbances are composite actions, which will facilitate the main objective of supporting the weight of the system. As such, they are the immediate functions below “Support, Stabilize – Materials, Object Solid”.

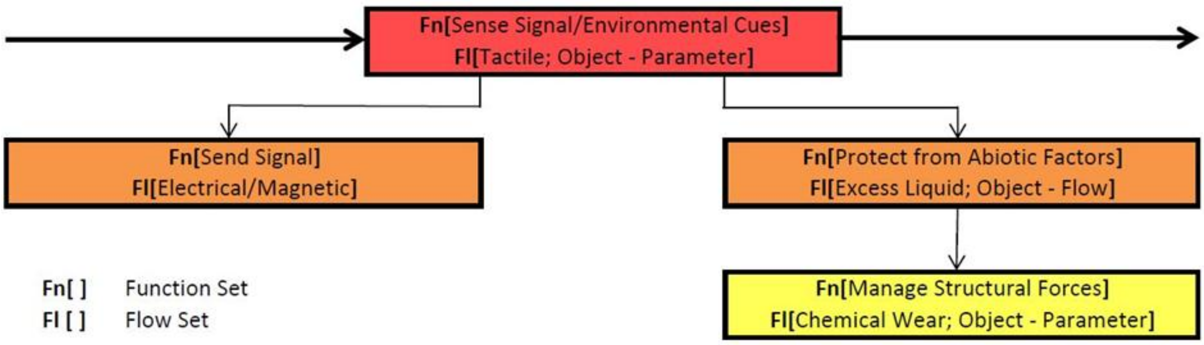
Regulation (correspondents “control, equalize, limit, maintain”) is the NIST representation of the generic control of the mechanism’s clamp – that is, the enabling and disabling of the actuating components. Actuate (correspondents “enable, initiate, start, turn-on”) encapsulates the autonomous clamping facility requested by the client. It may be seen, then, the latter is a subsidiary function of the former, as the manual control over the clamping state is more integral to the design functionality than the automatic activation. It is thus placed in the third function tier in the hierarchy. Along this cascade are located the functions which relate to the facilitation of automatic operation, represented within the NIST problem set under the Signal group. The flow of data is generated within the signal functions such as Detect and Indicate and passes to the function block enabling the clamp actuators. As such these elements may be categorized as subsidiary functions contributing to the descriptor “Control, Actuate – Material, Solid, Object”. Preventing degenerative chemical processes such as corrosion was not an explicit stipulation of the client however it is an implied necessity in achieving water resistance. It is therefore viewed as a sub-function to the descriptor “Magnitude, Stop, Inhibit – Material, Liquid”.

The NIST problem set hierarchy has been constructed in deference to the contribution of each element to the abstract objective of the mechanism. As such, it is concluded the critical function is “Support, Stabilize – Material, Object, Solid”, and the remaining constituents have been arranged in a manner representative of their ability to facilitate this critical function. […]

3.4.2.2 Step 2: Reframing the Problem

Starting to the technical problem described in NIST terms the application of the correlation matrix provided for the translation of the problem into the Biomimicry Taxonomy (BT) correlates the specific terminology of the two systems based upon both the *function* and *flow* of each element. The results are presented in Figure 3.7

Figure 3.7 The reframed problem hierarchy in the Biomimicry Taxonomy



Translated from the element "**Signal, sense, detect – Material, solid, object**", the generation and handling of a tactile or pressure signal would be capable of facilitating, in conjunction with structural constraints and requirements, the following *six* functions:

- ❖ Actuation of clamp
- ❖ Detection of clamping point
- ❖ Location measurement
- ❖ Status indication
- ❖ Stabilisation of pumping system
- ❖ Securing of pumping system

3.4.2.3 Step 3: Natural Source of Inspiration Search

Given the above considerations and analysis it is therefore concluded that, due to its influence upon the greatest number of the mechanism's functional aspects and the availability of information from the AskNature.org database the main function for browsing the database AskNature.org is:

Signal, sense – Tactile; object, parameter

[…] Four criterions have been derived as a comprehensive manner by which the relevance of an AskNature article may be modelled, with regards to the pump system rescue mechanism. Each of these is marked in the range 0 to 10, with 0 indicating no relevance and 10 indicating perfect relevance. Furthermore, each is prescribed a weight denoting its relative importance within the matrix evaluation system, allowing the more critical factors to take precedence in the final score attributed to each element. The aspects are:

Functional similarities **Weight: 40%**

This describes how close the natural solution's function and flow imitate the intentions of the main function of the BT set. The scope of this criterion extends to: *what* form the trigger or environmental cue takes; *what* kind of signal is generated (i.e. electrical); *how* the signal is generated; *how* the signal is handled. It is accorded the greatest significance of 40%, as the function of the source of inspiration is the critical determinant in translating a natural solution to the design.

Environmental similarities **Weight: 25%**

The similarities of environments in which the natural solution and the pump system rescue mechanism function include aspects such as moisture, temperature and pressure. A weight of 25% is attributed because high correspondence would be convenient in designing the mechanism, and there is an ability to adapt a biological solution for a different atmosphere.

Scalability of solution **Weight: 30%**

Under this consideration, the viability of altering the *magnitude* of the natural solution is evaluated. This allows for the delineation between micro and macro biological functions, and the simplicity with which natural solutions can be resized to compensate for increased forces. Influential weighting of 30% is allocated due to the fact the source of inspiration will almost certainly *require* scaling to suit the mechanism, and that without scaling the effectiveness of the system will be impacted in terms of reliability, accuracy and functionality.

- **Technological foundations** **Weight: 5%**

The technological factor represents the current state of art with regards to practical measures by which to implement the natural solution. This extends to the availability of sensor and switch types and sensitivities, signal-handling processors and configuration methods. The more 'iterative' a design process, by which existing structures and technologies are adapted to suit a new purpose, the more likely the mechanism will prove to be reliable, simple to fabricate and maintain and, overall, inexpensive. The score from this aspect is intended as an estimate of the simplicity with which the biological solutions might be implemented in reality. The evaluation of this aspect is given a weight of 5% as adaptation of existing technologies is convenient and ought to be considered but should by no means drive or motivate the conceptual design.

The sum of the four scores listed above will determine the rank of each article found under the Biomimicry Taxonomy category *Process Information: Sense signal/environmental cues – Tactile*. Of these, the three of highest value will be selected to progress with in the modelling process. In order to verify that the data is truly relevant to the topic of the conceptual design, a minimum score of 7.5, denoting a 75% correspondence with an 'ideal' article, is required to qualify for modelling. Should it be found that any of the items ranked first through third score lower than this threshold, a second main function may be derived or further branches of the Biological Taxonomy investigated to establish sources of inspiration with greater relevancy.

[…]

The descriptions about the NSoI are scored on each criterion as aforementioned, and the weighted values summed to deliver an overall rank indicative of the relevance pertaining to the functionality of the conceptual design. The raw score is first given, and the adjusted score provided in brackets within the same table element; i.e. RAW SCORE (WEIGHTED SCORE). Adjustments are calculated to a single decimal place. The overall score is the sum of the weighted values of the component criteria. Articles qualified for modelling further along the Bio-Inspired Design process, are highlighted in Table 3.31

Table 3.18 Ranking of the NSoI extracted by the AskNature.org by the prescribed criteria

	NSoI Name	Function	Environment	Scalability	Technology	Overall Score
1	Sensilla detect strain and load changes: insects	5 (2)	3 (0.8)	3 (0.9)	6 (0.3)	**4.0**
2	Plant growth responds to touch: wall cress	0 (0)	7 (1.8)	1 (0.3)	3 (0.2)	**2.3**
3	Hairs sense environmental cues: insects	7 (2.8)	5 (1.3)	8 (2.4)	8 (0.4)	**6.9**
4	Cuticle hole detects strain and load changes: insects	8 (3.2)	5 (1.3)	8 (2.4)	8 (0.4)	**7.3**
5	Sensitivity captures insects: Venus flytrap	9 (3.6)	8 (2)	9 (2.7)	9 (0.5)	**8.8**
6	Adapting swimming technique: lamprey	0 (0)	8 (2)	1 (0.3)	6 (0.3)	**2.6**
7	Fingertips sensitive to fine textures: humans	3 (1.2)	5 (1.3)	6 (1.8)	4 (0.2)	**4.5**
8	Snout detects pressure: star-nosed mole	8 (3.2)	9 (2.3)	7 (2.1)	7 (0.4)	**8.0**
9	Bill skin detects pressure: platypus	7 (2.8)	8 (2)	8 (2.4)	7 (0.4)	**7.6**
10	Congregating and physical stimulation trigger swarming: desert locusts	0 (0)	2 (0.5)	2 (0.6)	6 (0.3)	**1.4**
11	Pollen release triggered by bird landing: mistletoe	6 (2.4)	6 (1.5)	8 (2.4)	8 (0.4)	**6.7**
12	Whiskers detect details: mammals	5 (2)	5 (1.3)	5 (1.5)	7 (0.4)	**5.2**
13	Skin lights up when touched: swimming sea cucumber	4 (1.5)	8 (2)	8 (2.4)	8 (0.4)	**6.3**
14	Chemical defences protect from parasites: tobacco	1 (0.4)	4 (1)	2 (0.6)	4 (0.2)	**2.2**
15	Water channels prevent cellular rupture: Staphylococcus aureus	0 (0)	8 (2)	2 (0.6)	6 (0.3)	**2.9**

The lower limit for the acceptance of the NSoI is 0.75. In addition, it may be seen there exists a substantial gap between the selected topics and the majority of the remaining items, suggesting the scoring mechanism implemented functioned effectively in distinguishing the respective relevance of each. […]

3.4.2.4 Step 4: Defining the Nature's Solutions

From the evaluation of the fifteen descriptions available via the AskNature database under the matrix above, three NSoI have established themselves as the most relevant:

1. Sensitivity captures insects: Venus flytrap
2. Snout detects pressure: star-nosed mole
3. Bill skin detects pressure: platypus

For each of the above-mentioned natural systems the designer has developed the functional-causal model (see Appendix E).

3.4.2.5 Step 5: The Principle Extraction

The process for extracting the crucial or applicable information of the inspiration sources and their models is based upon the guidelines proved within the Problem-Solving Methodology. This rule set deconstructs data into four distinct categories i.e. *Function, Behavior, Structure and Morphology*. In turn, specific design considerations are associated with each aspect through the research to aid in direction the implementation of the natural system in the final conceptual solution.

Table 3.19 Matrix of information extraction from the natural sources of inspiration

NSoI	Nature's solution	Category
Venus flytrap: Sensitivity captures insects	**Trigger hairs**	Function
	Leaf geometry	Behaviour
Star-nosed mole: Snout detects pressure	**Epidermis**	Structure
	Eimer's organ	Behaviour
Platypus: Bill skin detects pressure	**Mechano- receptors**	Function
	Electro-receptors	Function

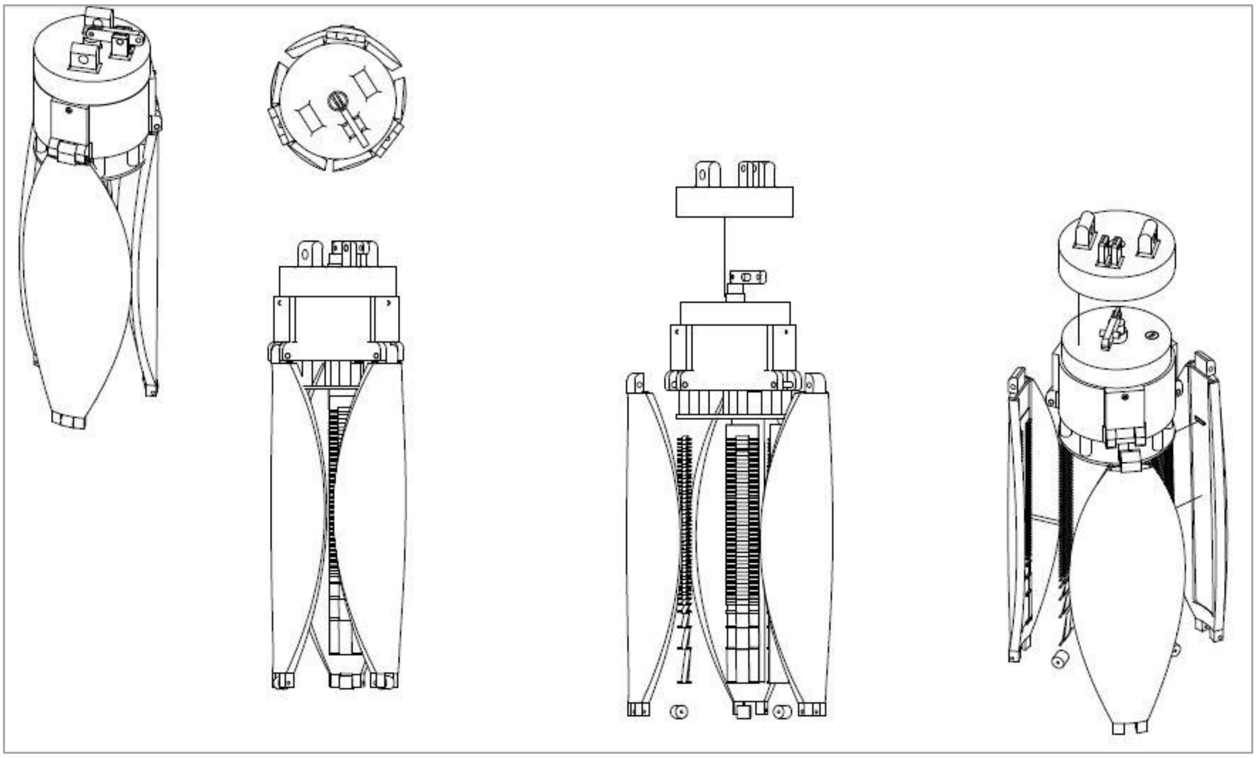
3.4.2.6 Step 6: The Design Phase

Upon completion of the extraction of Nature's solution information, the Bio-Inspired Conceptual Solution has been designed through the application and adaptation of function and mechanism from the NSoI.

3.4.3 - The Bio-Inspired Conceptual Solution

The pumping system retrieval mechanism functions via two main actions; the control of clamp actuation and the physical clamping of the pipeline. As such, it was deemed most crucial these are the primary focus of the Bio-Inspired Design aspects. The former required a tactile stimulation, ostensibly some form of pressure applied to a sensor, which would instigate a secondary action further along the workflow procedure. Under the problem definitions, this was generalized by the NIST and BT sets respectively as *signal, sense, detect – material, solid, object; sense* and *signal/environmental cues – tactile; object – parameter*. From the NSoI, models and the information subsequently extracted it was found three options from three separate sources existed to accomplish the tactile sensing. From the Venus flytrap there was the trigger hairs, the platypus provided a push-rod array of mechano-sensory receptors and the Eimer's organ and epidermis structure was derived from the star-nosed mole's unique snout.

Figure 3.8 Bio-Inspired Conceptual Solution of the rescue mechanism – overview drawing



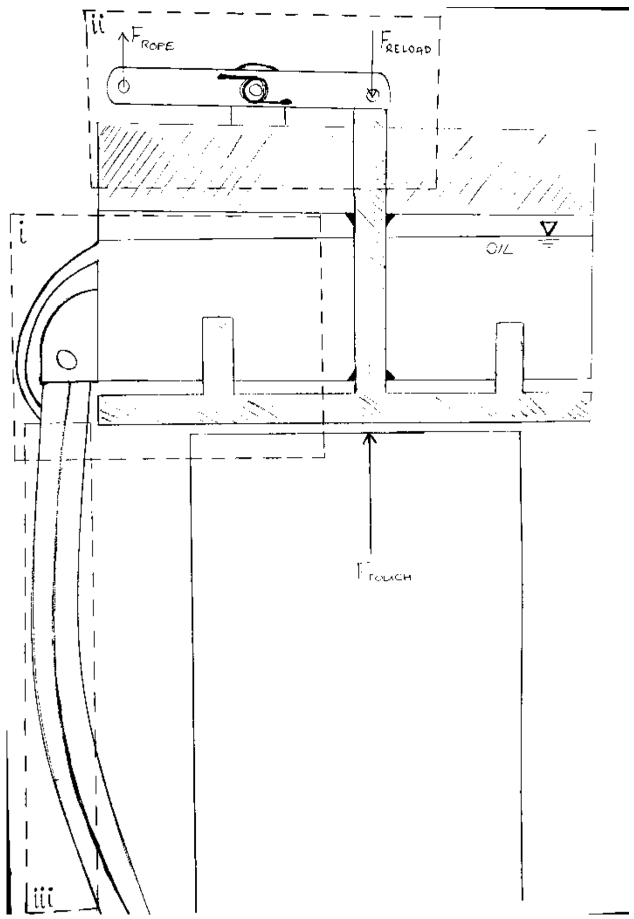
3.4.3.1 Approximate description of the technology

[…] The generic functionality of the conceptual design is the retrieval of a pumping system from below ground. It is to accomplish this through a clamping mechanism actuated by an environmental signal. Figure 3.10 below shows a sketch of the proposed device. It consists of the following components:

- Support ring (capped)
- Pressure plate
- Three toothed clamp arms
- Lever-based spring release mechanism

The structure of the conceptual design is based around a central support ring to which all components are affixed. The lever arms responsible for securing the pipeline are hinged near the bottom face of the support ring, and the pressure plate's eight push rods are inserted within eight corresponding shafts within the ring. These extend through to a set of pistons, which interact, with a chamber of hydraulic fluid, also part of the design of the support ring. […]

Figure 3.9 Conceptual sketch of mechanism

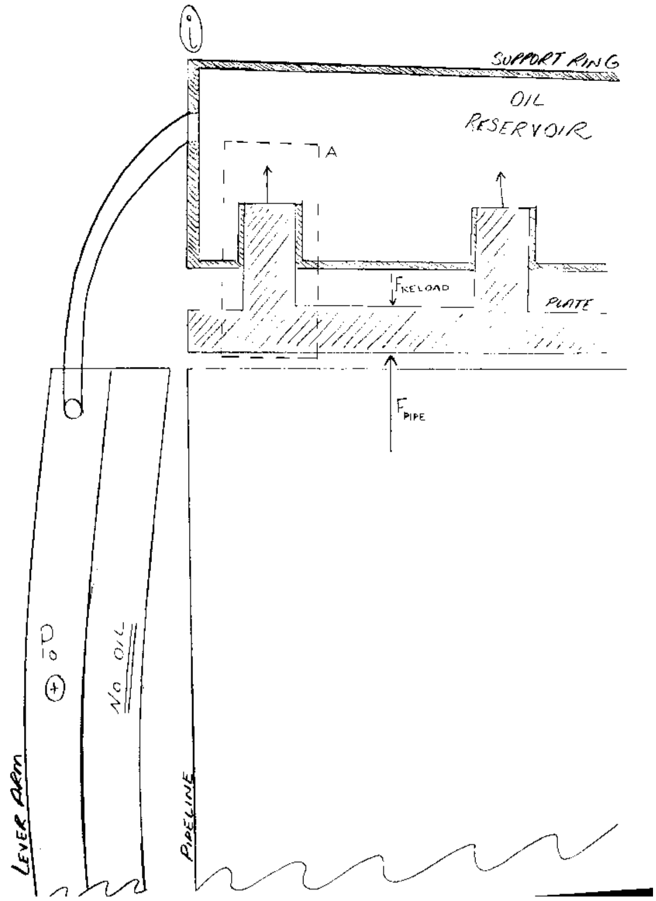


3.4.3.2 The working principle

[…] A release mechanism operated by a control rope and reset via a spring about the pinned center of the lever (Figure 3.12), is affixed atop the support ring lid. This enables the clamp to be disengaged manually from the surface. The mechanism operates by inserting it into the excavated hole with the three clamp arms *outside* the pipeline. As the clamp descends, the hinged levers are able to navigate about rope nodes and probes, which extrude from the pipeline's regular diameter. This is also assisted by the inclusion of small wheels at the base of each arm so as to provide as smooth travel as possible in its descent.

The pressure plate (noted in Figure 3.10) is the point of contact between the clamp mechanism and the pipeline. Founded upon the principles of the platypus bill and the internal mechano-sensory organs, the plate is connected to eight push rods arranged equally about the circumference of its upper face. These are inserted into guides within the confines of the support ring and press in turn against pistons (Figure 3.11). A critical aspect of this particular component is the flexible O-ring used in order to achieve a seal between chamber and piston whilst also allowing slight oscillation.

Figure 3.10 Conceptual sketch of detail – Pressure transfer system



In Figure 3.11 this is displayed as the black sections on either side of the piston. The force of the pressure plate affects the distribution of the hydraulic fluid within the support ring chamber, pushing it into the outer section of the lever arm. The increase in pressure instigates a process known as snap buckling, in which the arm passes from a stable convex state into a bi-stable state slowly, and then rapidly snaps across into a concave state, based on the operation of the Venus flytrap enclosure. Upon lifting, the teeth which line the inside face of each arm, at varying lengths depending upon their position down the length (close to the base equates to longer teeth); 'bite' into the PVC pipeline and secure the pumping system for ascension. With a concave geometry, the ends of the lever arms curve outwards, towards the earthen walls of the pump hole. The wheels at the base of each arm now assist in achieving a smooth lift, allowing the clamp to navigate around the irregular surface. Integral to the operation of the mechanism is the pressure of the outer arm relative to the inner.

Figure 3.11 Conceptual sketch of detail – View A piston configuration

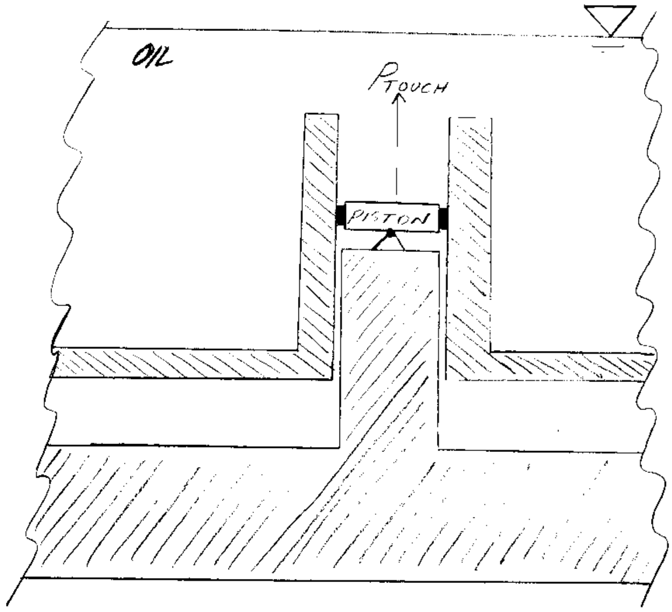
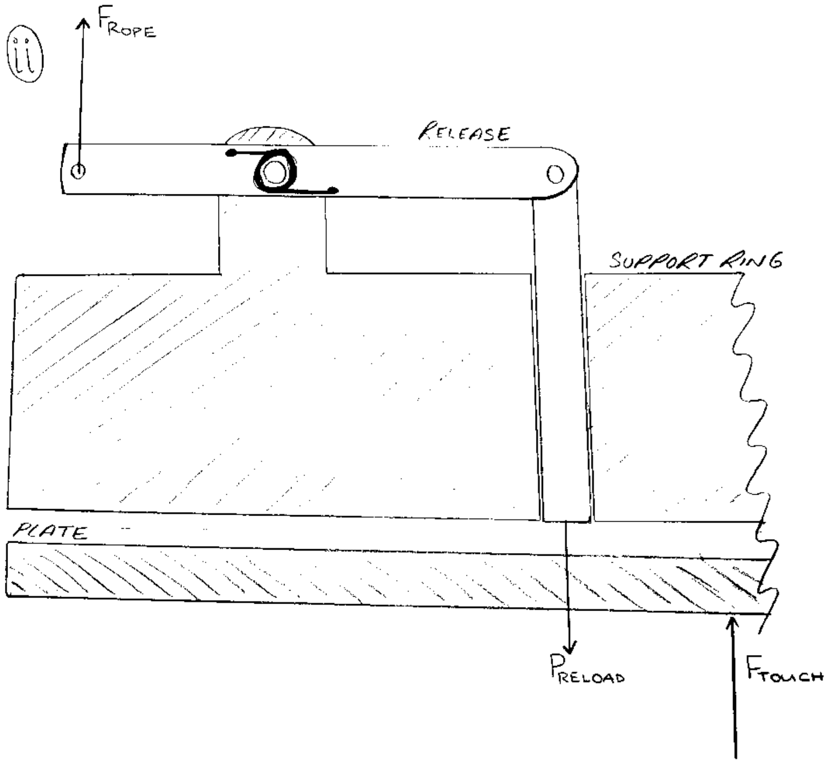
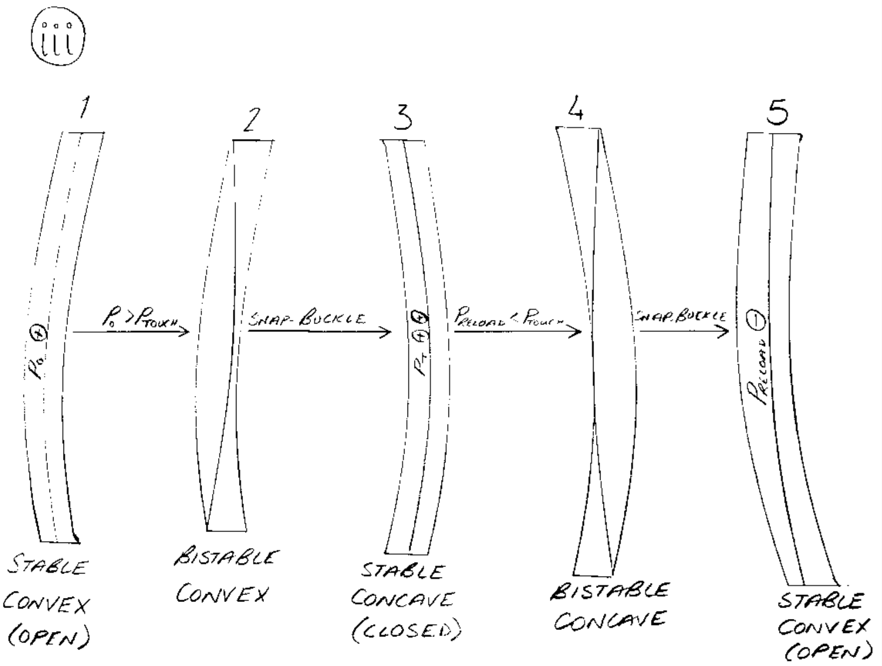


Figure 3.12 Conceptual sketch of detail – Release mechanism



The relationships are displayed in the process diagram Figure 3.13. The inner pressure may be assumed to be zero as there is no fluid movement within it during the clamping phase. The rest pressure P_0 occurs when the arm is in a stable convex state, and the system is not activated. Upon depression, the flexible internal wall buckles and causes the arm to assume a bi-stable convex state, wherein with a further minimal depression of the pressure plate it snap-buckles into a stable concave state, analogous to ‘closed’ in this instance. Upon pulling the control rope, if the force exerted (F_{RELOAD}) is in excess of the force of the pressure plate opposing it (F_{TOUCH}) the plate will extend out of the support ring, and the pressure in the clamp arms will reverse. The flexible walls buckle *out*, and the arm assumes a bi-stable concave position. Further displacement of the plate, as before, causes the outer faces to flex into a stable convex state. All this is dependent upon the pressure plate being pushed by the pipeline *into* the body of the support ring. The release mechanism, a pinned lever attached to a control rope running to ground, is thus designed to push the pressure plate in the opposite direction, reversing the pressure within the three clamp arms and in turn the snap-buckling process. Using the disengage rope a surface-based operator is able to reset the system without raising the mechanism above ground. Once reset, it is able to be reused immediately, as the spring returns the lever to its original position and permits the pressure plate to again affect the hydraulic system and repeat the clamping action. […]

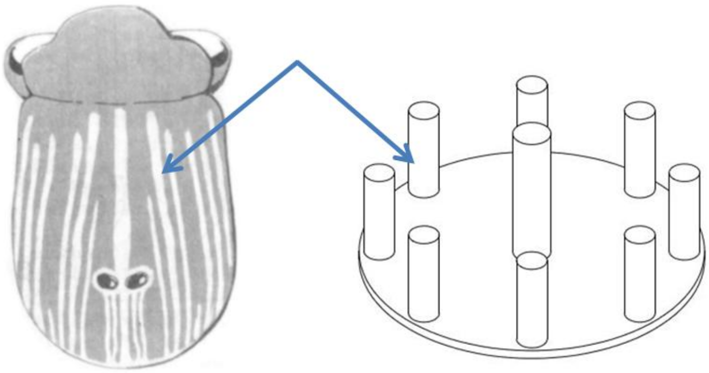
Figure 3.13 Conceptual sketch of operation of snap-buckling clamp arm



3.4.3.3 The form

[…] The platypus bill’s tactile receptors possessed a morphology, which was easily scaled to account for said pressures and could be adapted to increase robustness. Furthermore, the mechano-sensory receptors are used solely to detect environmental objects and provide this information to the cortex in order to precipitate action on behalf of the platypus. As such, the biological solution was imminently applicable in this capacity. An array of push rods connected to a plate, analogous to the array of fiber rods, which contact the outer skin of the bill, was devised. Much like the bill itself, upon activation (contact) the pressure plate-push rod does not engage in further interaction with the environment itself but instead instigates a new action, described below.

Figure 3.14 Comparison between Nature's solution and technical implementation



The second most crucial aspect of the mechanism is the manner by which the clamping is performed upon the pipeline and pumping system. This must be capable of applying sufficient force to secure the entire system and support it as it is raised to the surface and lowered to the water table. This accounts for the elements of the NIST problem set *support, stabilise – material, solid, object* and *support, secure – material, solid, object*. From the Ask Nature database only a single biological solution was obtained; the snap-buckling characteristics of the Venus flytrap's leaf enclosure in the capture of its prey. As may be seen from the evaluation matrix of the NSOI, this was the highest scoring of all inspirations derived from the reframed problem set. This performed the ideal action for application in a technical manner of a set of hands 'snapping' shut in response to a tactile environmental signal.

Figure 3.15 Comparison between Nature's solution and technical implementation

The clamp arms are clearly designed to imitate the geometry of a leaf in order to more closely resemble and implement the snap buckling achieved by the Venus flytrap. The most complex aspect of adaptation came in causing the three arms to accomplish the closing motion by change shape from convex to concave. In the biological solution, this is done by altering the distribution of water across the leaf, and in turn the strain across the x-axis until mechanical buckling occurs. A hollow arm structure split in half by a flexible inner wall was devised, the outer chamber of which is filled with hydraulic fluid. Depression of the pressure plate presses an array of pistons (Figure 3.11) into hydraulic chamber of the support ring, increasing the pressure within the outer section of the clamp arm. The inner wall flexes inwards in response, creating a bi-stable state at which point a slight application of further pressure from the push-rod structure causes snap buckling, imitating the Venus flytrap. Release of the pressure plate simply reverses this operation (Figure 3.13). […]

3.5 - Experiment Nr. 3

Designer Nr. 2 (See Table 3.7 for the details) has applied the problem solving methodology on a Tie Mechanism for Underwater Pumping Systems. The problem has been presented as test case in Table 3.3

Motivation: the standard systems that exist for the tie present several problems. First, they are made highly and easily deformable. This deformation i.e. usually plastic do not ensure a sufficient clamping force to support correctly the “column of wires” of the underwater pumping system. Moreover, they cannot be reused and for each maintenance operation, they have to be changed.

Goals: Develop a Bio-Inspired *Conceptual* Solution of a non-standard tie mechanism to use in underwater pumping systems through the implementation of Nature’s solutions.

In order to achieve this goal to the designer has been asked to apply the methodology by following a set of tasks:

- Develop a requirement list following the (Pahl et al., 2007) approach
- Apply the entire methodology following a time-line and using the set of tools provided
- Develop a Bio-Inspired Conceptual Solution that fulfil the requirement list
- Write a report on the entire process
- Write a report on the conceptual solution
- Compile a questionnaire about the method

The final results have been presented in (Sutter, 2013).

3.5.1 - Case Test B – The Technical Problem

In order to obtain a standard starting point to all the experiments according to (Pahl et al., 2007) it has been asked to the experts/customers to fulfil a standard questionnaire about the problem. In fact, the questionnaire with the answers of the experts has been given to the designer as a base to develop the requirements identification.

Questionnaire

1. **What are the objectives that the intended solution is expected to satisfy?**

    ✓ *Ability to fasten/tie the electrical wire, the rope and the water tube*
    ✓ *Ability to develop a sufficient clamping force*

2. **What properties must it have?**

    ▪ *Ability to resist to water*

- *Ability to block even larger objects as rope nodes and probes*
- *Ability to create a stiffening of the structure due to their combination*
- *High capacity for deformation without breaking*
- *Possibility of mounting without tools*

3. **What properties must it not have?**

- *Complexity*
- *High cost*
- *Difficult installation*

Furthermore, the specifications about the dimensions of the wires and some pictures have been given to the designer.

Figure 3.16 Standard tie mechanism used in the underwater pumping systems

Distribution of the ties: 3 every 3 [mt]

The first one ties it all together (wire-rope-tube) then the second (rope-tube) and the others with a specific distribution - see the pictures.

In Figure 3.17 it is possible to note the tool used for the operation of realizing the clamping force in the tie.

Figure 3.17 Standard tie mechanism used in the underwater pumping systems and clamping tool

3.5.2 - The Problem Solving Process

Starting to the questionnaire, the pictures of the system and some meeting with the expert the requirements list has been developed and it is provided in the (Appendix A).

The outputs of each step that have been extracted from (Sutter, 2013) are reported in the following sub-sections.

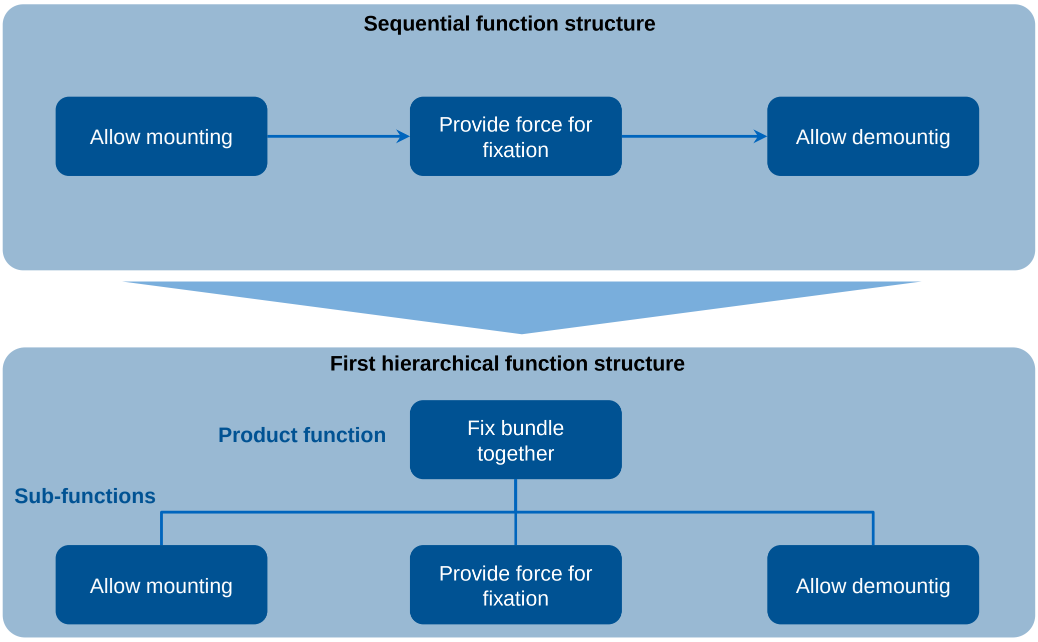
3.5.2.1 Step 1: The Problem Definition

[…] The aim of step 1 is to express the problem in functional terms in order to prepare the foundation for the translation into biological terms in step 2.

Before the problem could be described with the formal NIST-FB, it was first expressed in a more intuitive language. Therefore, the most abstract functions were derived from the requirement list. Then they were expressed in a sequential function structure, which was afterwards used to create the highest levels of a first hierarchical function structure (Figure 3.18) and thus to find the product function and the highest sub-functions.

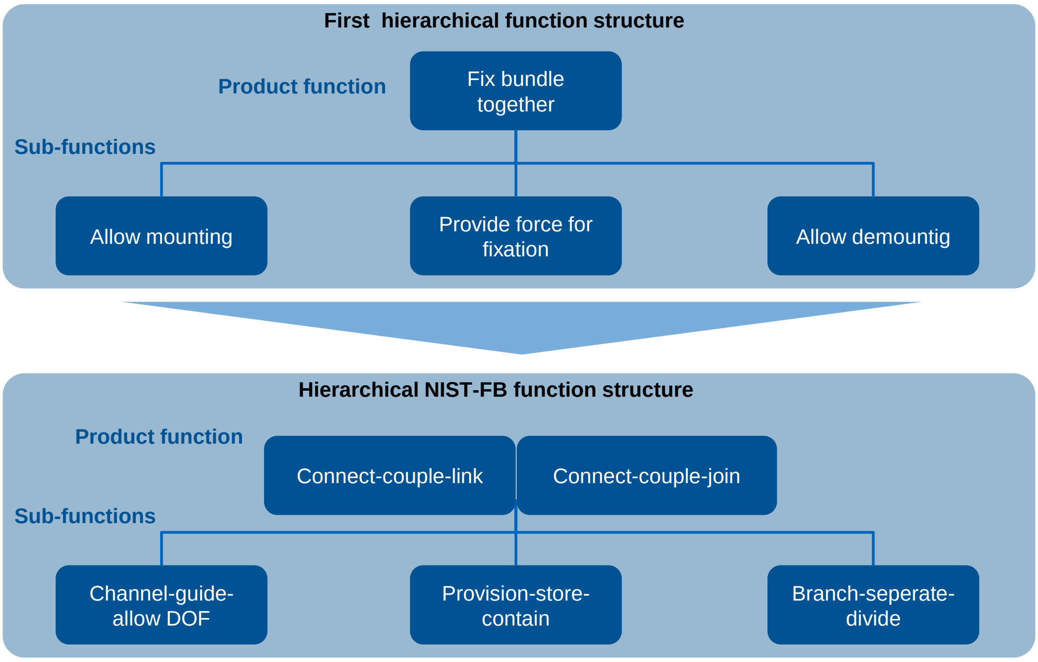
This hierarchical function structure has been then compared again with the requirements list in order to ensure that all the requirements were considered and could be allocated to a sub-function within the model. After this was checked, the translation of the current product function and the three sub-functions into NIST-FB was prepared by searching the table of the NIST-FB for convenient function vocabulary.

Figure 3.18 The hierarchical function structure derived from a sequential function structure



The NIST-FB provides functions and flows in order to describe the sub- and product function. In order not to limit too strong the diversity of possible natural solutions, the sub- and product function in this thesis will not be defined by flows. Thus, the translation into NIST-FB was achieved by only selecting the most suitable functions. In this case the category correspondents was especially helpful as it offered a broad choice of technical terms which supported and simplified the choice of the three classes primary, secondary and tertiary.

Figure 3.19 Translation of colloquial functional terms into NIST-FB functional representation



The result of this translation of the first hierarchical function structure into NIST-FB is that there was one possible translation for each of the three sub-functions and two possible translations for the product function (Figure 3.19).

Now that the most important functions were available in NIST-FB, the problem has been defined in a standardized technical way, which allows further steps to be conducted. […]

3.5.2.2 Step 2: Reframing the Problem

[…] Therefore the adopted tool of a correlation matrix was given, containing the NIST-FB terms as well as the BT expressions.

At first, the two product functions have been translated from NIST terms by searching the given BT equivalent (Figure 5-3). The results were two problem descriptions in BT terms, which together included the number of 147 NSoI. This lead to the decision not to translate the NIST-FB sub-functions (Figure 3.19), too, as a higher amount of NSoI would have been too extensive to work on with.

Figure 3.20 Translation of NIST-FB into BT terms

NIST-FB				BT	
Primary	Secondary	Tertiary		Group	Sub-Group
Connect	Couple	Link	▶	Move or stay put	Attach
Connect	Couple	Join	▶	Make	Physically assemble

Hence, no further activity had to be applied within this short step. […]

3.5.2.3 Step 3: Natural Source of Inspiration Search

[…] As the previous goal was to find the correct BT expressions for the problem at hand, the task of this step is to search within the 147 NSoI of these BT terms, the ones, which have the potential to fulfil the product requirements in the end.

At first, all evaluation criteria were developed in order to determine which of the NSoI were the most appropriate for using their natural working principles in the product. These criteria are further explained in the following.

- *Scale of the phenomenon:* This refers to the size of the NSoI. Approximately similar dimensions to the ones from the requirements list might simplify the later technical realization of the natural working principles.

- *Analogy between the industrial example and our problem:* For many of the potential NSoI on AskNature.org possible industrial utilization suggestions are offered. Thus, the ones with the most similar use cases concerning the given problem were evaluated best in this point.
- *Environmental conditions for the NSoI:* This criterion evaluated the conditions, which influence the NSoI in their natural environment. Here the ones, which have to withstand water and dirt most, were rated best.
- *Physical implementation:* By this, it is expressed in which way the natural working principles are realized by the NSoI and how suitable they seem for a use in the technical product at first sight. As there is no product idea yet, this criterion was valued intuitively. For example a plant with leaves embracing cylindrical shaped branches appeared more suitable for the technical problem at hand than a nautilus shell which grows step by step.

Then these criteria were put in a direct comparison to each other to find out their relative importance. This was conducted in a pairwise comparison. Hence, it was found out that the scale of the phenomenon had the greatest influence on the appropriateness of the NSoI. Otherwise, the environmental conditions were rated as least important because a product can be adapted to them without great effort by changing the material.

Table 3.20 Pairwise comparison of the evaluation criteria

More important than?	a)	b)	c)	d)	Sum	Ranking
a) Scale of phenomenon		2	2	2	**6**	1
b) Analogy between industrial example and our problem	0		1	1	**2**	3
c) Environmental conditions for the NSoI	0	1		0	**1**	4
d) Physical implemtation	0	1	2		**3**	2

2 more important
1 equally important
0 less important

Consequently the importance of the criteria was settled. Besides, it was necessary to also have a scale for the fulfilment of these criteria by the NSoI. For this the Likert-type scale from (Vagias, 2006) has been deployed. Thereby the level of appropriateness was weighted in values from 1 to 7. While 1 said that the specific NSoI was absolutely inappropriate concerning a criterion, 7 is the best grade and declared the NSoI as absolutely appropriate in regard to the criterion.

Then the 147 NSoI were evaluated by the fulfilment of the criteria above (see first column of every NSoI in Table 3.21). The basis for the knowledge about these fulfilments was the information provided on AskNature.org for each NSoI. This information there is structured into four main sections. The first is a one-liner roughly describing the overall phenomenon, which characterizes the NSoI. Afterwards knowledge that is more detailed can be taken from a summary text, which already describes the natural working principles more detailed. An excerpt below provides a quoted scientific text about the NSoI. The fourth section which has greater relevance for this step presents application ideas and industrial sectors where it the natural principle might be used in products. Besides these four main sections also other additional information like pictures, a list of experts, references and the scientific name of the NSoI are given.

After all the 147 NSoI were valued from concerning the criteria, this appropriateness from 1-7 was multiplied with the importance from 1-6. This lead the overall weight of the single possibilities (see second column of every NSoI in Table 3.21)

Table 3.21 Evaluation of all the NSoI concerning the criteria and their importance

		Possible NSoI							
Evaluation Criteria	Importance	NSoI 1		NSoI 2		…		NSoI 147	
Scale of phenomenon	6	6	36	4	24	…	…	1	6
Analogy between industrial example and our problem	2	7	14	4	8	…	…	1	2
Environmental conditions for the NSoI	1	6	6	4	4	…	…	6	6
Physical implementation	3	5	15	5	15	…	…	1	3
		24	**71**	17	**51**			9	**17**

Subsequently a plausibility and sensitivity analysis was conducted. Therefore, the criteria and their importance were reassessed and finally considered as logic. Moreover the values of the importance were checked and varied again which showed that the highest ranked NSoI were still within the best.

Then then four highest ranked were chosen in order to prepare for the next step. The quantity of four was taken because it was considered as a broad enough range of sources and still a few enough number, which can be still handled. The first three of them were form the BT category “move or stay put - attach - temporarily”, while last one NSoI was from “make-physically assemble - structure”. Afterwards the information, as described above, of these four examples were taken from AskNature.org (a) and put into an extra text document, which could be used in the following. […]

3.5.2.4 Step 4: Defining the Nature’s Solutions

From the above-mentioned evaluation, the following NSoI have been selected:

1. Sticky proteins serve as glue: Blue mussel
2. Hooked beak snags flowers: Flower piercer
3. Low-energy perching: Mouse bird
4. Colonies survive floods: Fire ants

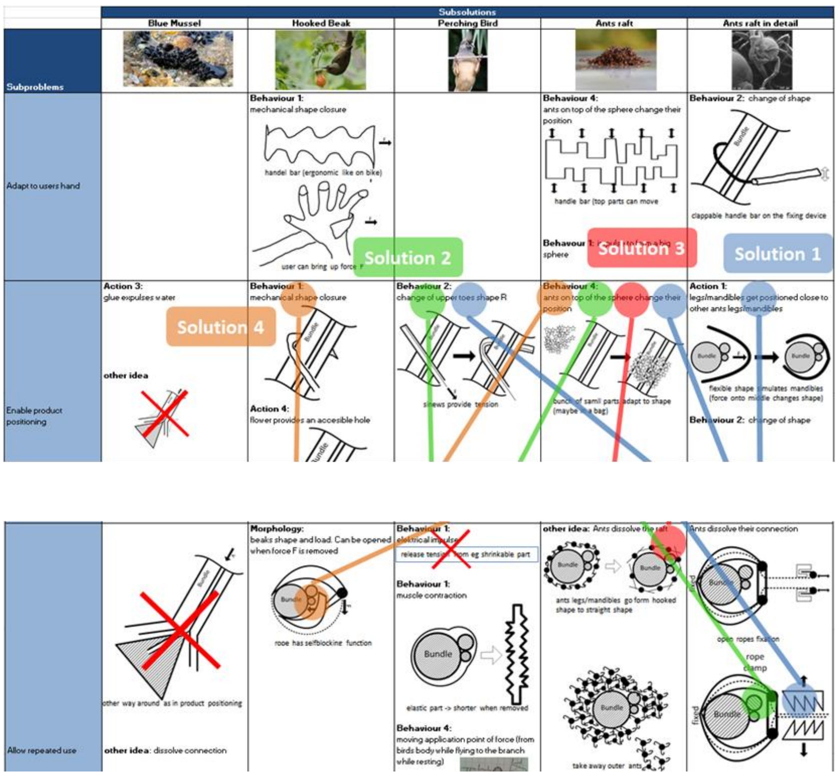
For each of the above-mentioned natural systems the designer has developed the functional-causal model (see Appendix E).

3.5.2.5 Step 5: The Principle Extraction

[…] After having completed the description of the NSoI with SAPPhIRE-DANE models in step 5, it was possible to extract natural working principles from these. In order to structure the working principles concerning the sub-functions, a morphological matrix has been used. On this way, it was possible to show clearly, which NSoI provided which working principle in order to solve a sub-function (Figure 3.21). These working principles can be *Actions, Behaviours, Structures, or Morphologies* from the SAPPhIRE-DANE models and were numbered accordingly to their position within these single models. Each phase has its number growing from 1 on from the left to the right. For example in Figure 3.21 the behaviour 2 is extracted from the second phase of the perching bird's model.

In the first step, the morphological matrix was filled by accurately searching the single SAPPhIRE-DANE models for natural working principles, which were capable of solving the single sub-functions. In a second step, these natural working principles were translated into engineering language by sketching convenient technical sub-solutions for them. Both the natural working principle as well as the possible technical sub-solution stands together in one place of morphological matrix. This step depended on the creativity of the operator of the method, which determined that not for every single natural working principle a technical expression was found. Nevertheless, most of the gaps in the matrix could be filled one by one with these technical sub-solutions. The bundle was always illustrated as three cylinders of different size. Depending on the situation, the bundle was shown either in a side perspective or in a top view.

Figure 3.21 Exemplarily excerpt of the morphological matrix



The result of this advance was a broad field of possible product solutions. So as to get the most adequate sub-solutions, the most inappropriate ones needed to be sorted out. Here an evaluation system based on

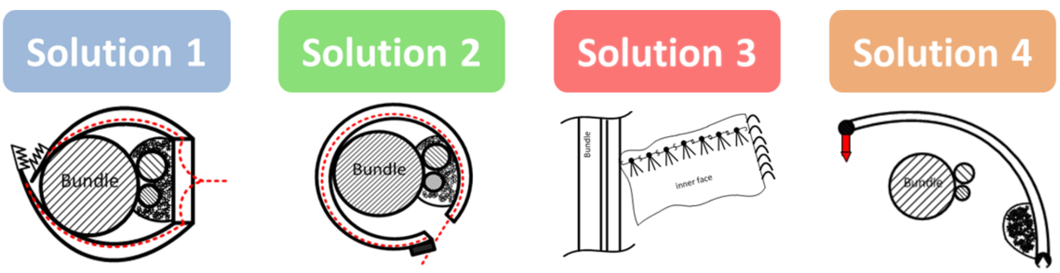
K.O. criteria was applied. In communication with the expert of the pumping system, the following K.O. criteria were worked out:

- *High technical complexity:* This means that a product consists of lots of different parts and occupies a high level of technology, which might be disadvantageous for embodiment design as well as for production. Moreover, the present solution of the cable ties offers, despite the disadvantages explained in the beginning of chapter 5, a design with low complexity. Thus, it is aspired to keep the new product design also as simple as possible.
- *High weight:* It is unwanted as a rope that must not be further stressed holds the whole bundle. In addition, more weight would complicate the process of letting the bundle down or pull it up again as these processes are carried out by handcraft.
- *Electrical current:* Regarding the fact that the product needs to withstand water, it is saver to abdicate electrical current. This reduces the risk of a collapse of the product function as well as the danger of injuring the user.
- *Closed shape:* The expert was also sure about the fact that a closed shape into which the bundle might have been pulled would increase the risk of damaging it. Besides, he considered it as too complex concerning the mounting process.

Based on those K.O. criteria the biggest part of the blue mussel´s sub-solutions were eliminated, which lead to the fact that it was not considered any more in the generation of the overall product solutions. The K.O. criteria also concerned several sub-solutions of other NSoI but because they mostly had a higher number of sub-solutions as the blue mussel, it didn´t suspend them from the possible overall product solutions.

After the morphological matrix was rethought and refined, the technical sub-solutions, which matched best to each other, were combined into four most promising overall product solutions.

Figure 3.22 The four Bio-Inspired Conceptual solutions obtained by combining the Nature's solutions collected in the morphological matrix



Besides the requirements list, a checklist of (Pahl et al., 2007) was used as a source for further and more general evaluation criteria which were not completely covered by the requirements list yet. Moreover, an additional criterion, which stood for the innovation degree of the different product solutions, was established. By deploying this criterion, it was possible to evaluate the product solutions concerning the number and kind of natural working principles they consisted of. This was necessary to be observed, as the product with the numeral majority and the more innovative working principles represents the BID.

Having completed the choice of evaluation criteria, they needed to be assessed in matter of their importance. This was achieved by conducting a pairwise comparison (Table 3.22) like in step 3. Only the importance of the additional criterion was difficult to compare to the others because it had a higher abstraction level as the rest of the criteria, which were more detailed and for practical use of the product. Thus, it was always set as equally important to each of the other criteria in order to achieve an average importance.

Table 3.22 Pairwise comparison of the evaluation criteria

More important than?	a)	b)	c)	d)	...
a) Geometry which doesn`t easily hook on rocks		2	1	2	...
b) Self explaining geometry for intuitive handling	0		0	2	...
c) Prevent relative movement inside the bundle	1	2		2	...
d) Few relative movement of the fixation product itsself	0	0	0		...
...	...	...	...	...	

2 more important
1 equally important
0 less important

After the criteria were weighted, the next task was to evaluate the four overall solutions with them. Here again the additional criterion was an exception. While the fulfilment of the other criteria depended mostly on estimation, the fulfilment of the additional criteria could be measured exactly.

Table 3.23 Exemplary depiction of the innovation determination of product solution 1

Solution 1

Natural working principle		NSol	Sub-function		Degree of innovation
Action	Action 1: legs/mandibles get positioned close to other ants´ legs mandibles	Ant raft in detail	Enable product positioning		3
	Action 3: legs/mandibles of different ants are firmly attached to each other	Ant raft in detail	Maintain inner tension		3
	Action 2: inner ants of the sphere are fixed in their position	Ant raft	Maintain bundle´s stability		3
Behaviour	Behaviour 2: change of upper toe´s shape	Perching bird	Enable product positioning		4
	Behaviour 4: ants on top of the sphere change their position	Ant raft	Enable product positioning	Allow barriers to slide by	4
	Behaviour 1: impulse (mechanical)	Ant raft in detail	Activate fixing mechanism		4
	Behaviour 3: legs/mandibles transmit force betw een each other	Ant raft in detail	Maintain pressure on bundle		4
					Sum 25

Therefore, the kind and number of natural working principles, which were used for each overall solution, were determined. Considering the work of (Howard et al., 2008) the behaviour creates the most innovative design output. Then comes function before structure. The morphology offers the fewest chances on an innovative design. These four categories were valued from 1-4. 4 represented the actions and thus offered the most innovation, while 1 stood for the few innovative morphology.

Thus, every used working principle extracted from nature received a certain value. For example in case of product solution 1 there were neither structures nor morphologies. The sum of the evaluation of innovation consisted only of actions and behaviours and had the value 25 (Table 3.23).

After all the criteria were clarified, the actual evaluation of the product solutions could be conducted. In this working stage (Pahl et al., 2007) advises to give values from 0-4 because for example 0-10 would simulate a degree of detail which is actually not given by the approximate description of the solutions in this phase.

Table 3.24 Evaluation of the four solutions with the weighted criteria

			Possible product solutions							
Evaluation Criteria		Importance	Solution 1		Solution 2		Solution 3		Solution 4	
Requirements list	Geometry which doesn`t easily hook on rocks	19	3	57	3	57	1	19	3	57
	Self explaining geometry for intuitive handling	15	4	60	3	45	2	30	2	30
	Prevent vertical relative movement inside the bundle	24	4	96	4	96	3	72	4	96
	Few relative movement of the fixation product itsself	12	2	24	2	24	3	36	2	24
	Not too high force for fixing necessary (easy going movements)	15	2	30	2	30	2	30	2	30
	Force on bundle is limited automatically	1	0	0	0	0	2	2	0	0
	Sufficient fixation force on bundle for horizontal stiffness	22	4	88	4	88	1	22	4	88
Checklist (Pahl et al. 2007, p. 193)	Function: enable product positioning (adapt to bundle´s shape)	18	3	54	4	72	4	72	4	72
	Safety: no possibility to hurt users hands	24	3	72	2	48	3	72	1	24
	Embodiement: low comlexity	9	2	18	3	27	0	0	4	36
	Ergonomics: movement effort for mounting (big or small movements necessary for mounting)	10	4	40	3	30	1	10	2	20
	Production: small number of simple components	5	1	5	2	10	0	0	4	20
	Production: easy variation of different lengths (with same production processes)	5	2	10	3	15	4	20	4	20
	Quality control: simple and reliable procedures	14	2	28	2	28	1	14	4	56
Additional criterion	Innovation degree of the product solution	14	4	56	3	42	2	28	1	14
			40	**638**	40	**612**	29	**427**	41	**587**

This 0-4 scale is taken from the VDI 2225 (1977) and has the following meaning concerning the fulfilment of the evaluation criteria:

- 0 unsatisfactory
- 1 just tolerable
- 2 adequate
- 3 good
- 4 very good

While the other criteria were rated by these values approximately, the results of the additional criterion were directly translated into the VDI 2225 (1977) scale. Hence, the highest degree of innovation, which was 25, was translated into 4, which stands for very good. The least innovative with 15 was valued with 1, which means just tolerable.

Afterwards all the 0-4 values of the criteria were multiplied with their importance and lead to the final evaluation result (Table 3.24). […]

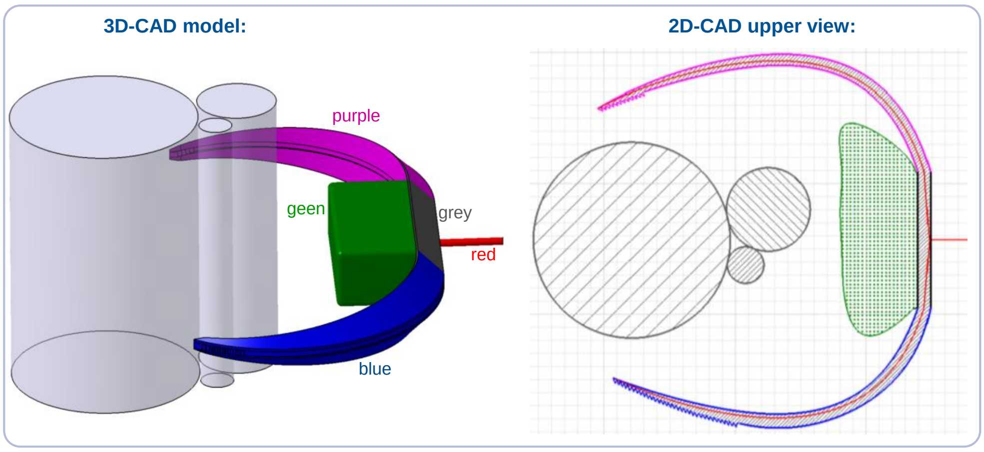
3.5.2.6 Step 6: The Design Phase

Starting from the results presented in Table 3.24) the product solution 1 was evaluated best with 638 points. In order to check for mistakes and on reliability, the plausibility and sensibility of the results were tested. Subsequently it was still definite that product solution 1 is the chosen product, which was to be further detailed and developed in the design phase.

3.5.3 - The Bio-Inspired Conceptual Solution

[…] As the simplified 3D-CAD model and the 2D-CAD sketch above show (Figure 3.23), the product consists of three main parts.

Figure 3.23 CAD models of product solution 1



3.5.3.1 Approximate description of the technology

[…] The most integrated part is the casing, which was separated in the three different sections of blue, grey, and purple. The blue and purple sections are the ones, which embrace the bundle and thus need a certain flexibility. Both of them have teeth near their end in order to hold to each other by clicking in place. Thus, the purple section has them on the inside while the blue one has them on the outside. These two sections are connected over the grey basis which doesn´t have to be as flexible as the blue and purple ones. The casing´s shape is added by an acute angle in order to further reduce the problem of hooking to rocks in the ground. The material of the casing is synthetics.

On the inner face of the casing, the green adaption part is connected to the grey basis. This adaption part has a flexible cover and contains many small fragments in order to adapt to the bundle´s shape. It might be fabricated of synthetics.

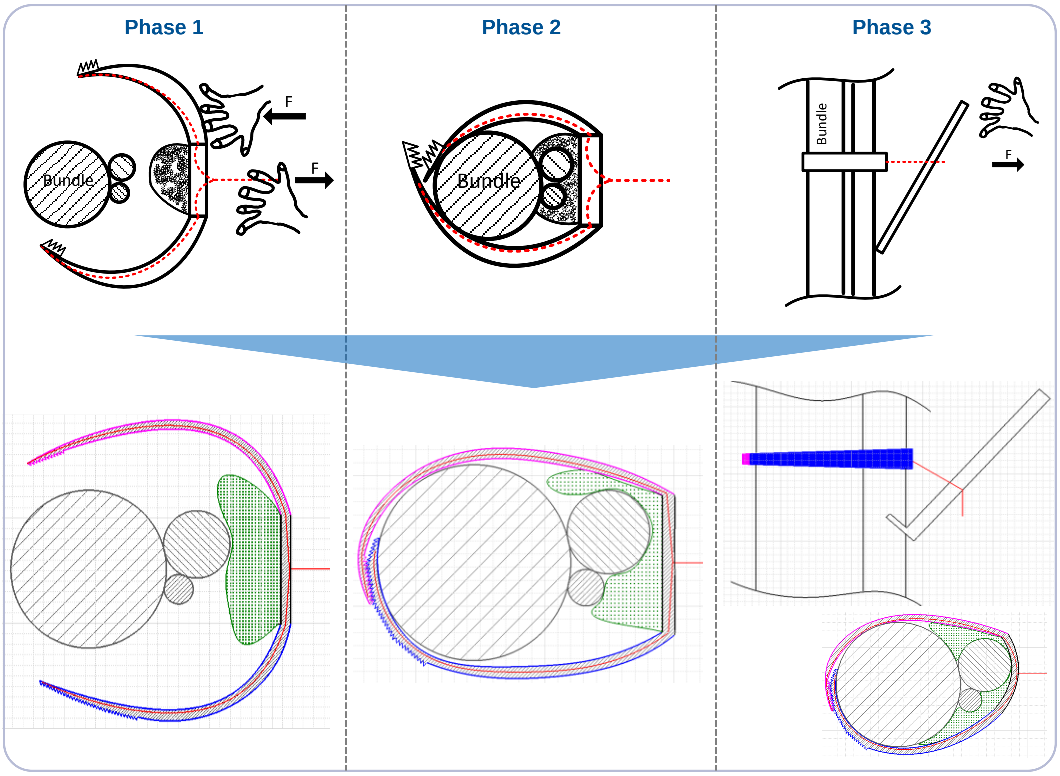
The sinew is illustrated in red and represents the third main part. It leads through an opening on the outer face of the grey part to the inside of the casing where it splits up in two threads of which each is firmly connected to the ending of one arm. As the sinew needs to endure strong tension, its material might be synthetics or even steel.

As the whole device, together with the bundle, is let down into holes with water, all of the applied materials must be waterproof. [...]

3.5.3.2 The working principle

Figure 3.24 shows the three working phase of the Bio-Inspired Conceptual solution 1.

Figure 3.24 Detailing the conceptual product solution 1



[...]

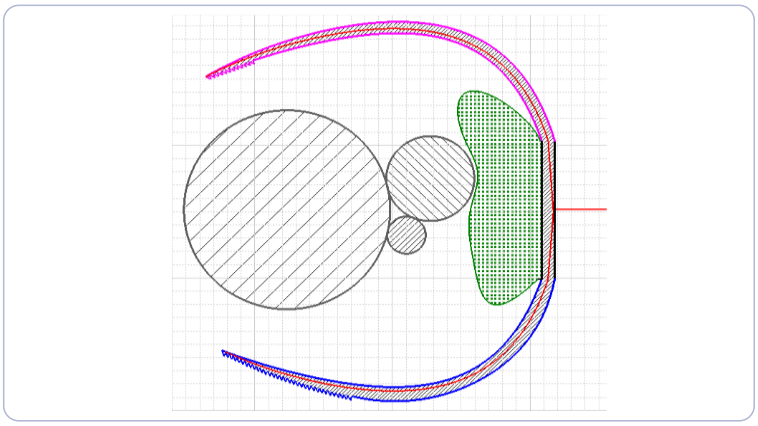
Phase 1

This phase is dominated by the sub-function enable product positioning, which means the possibility for the user to correctly hold the product in relation to the bundle. Moreover, a first change of shape of the adaption part to the bundle takes place (Figure 3.25).

In order to achieve this easy positioning relative to the bundle, the product is designed in the illustrated standard shape if it is not under tension. The shape, which looks similar to ant mandibles, causes a correct positioning intuitively. By arranging this position, the adaption part automatically gets in contact to the bundle and thus slightly changes its shape. On this way, the device can be brought into position in preparation to phase 2.

For the purpose of realizing an easy going positioning process, the small fragments inside the adaption part must change their shape without high necessary pressure. Therefore, its cover must also be flexible in order to allow these relative movements of the fragments inside. The material of the grey basis however is harder to deform in order to keep the same shape of the casing within this first phase.

Figure 3.25 Product with still opened shape



Phase 2

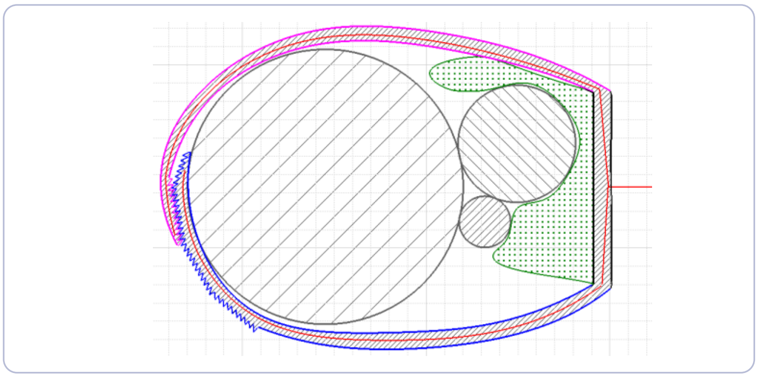
Here the focus still lies on the product positioning. Nevertheless, the positioning process has progressed and the first part of the activation of the fixing mechanism will take place as Figure 3.26 shows.

Concerning the positioning, the clasping of the bundle is easily fixed by hand and not by lever yet. Therefore, the two blue and purple counter pieces with the teeth need to bend around the bundle in order to click into place and to hold each other. To achieve this first fixation the operator uses one hand to push the device towards the bundle and the other hand to pull the sinew. On this way, it is possible to mount the product without the need to embrace the whole bundle and thus accomplish large or complicated movements. By conducting these tasks, also a further deformation of the adaption part is achieved. This means that the user already forced the adaption part into a close position to the bundle.

The material of the casing around the sinew must be flexible but especially the outer part mustn`t be able to be compressed. The inner casing might be deformed stronger and may even be compressed. Thus, it is guaranteed that the bending direction is correct and the product presses against the bundle. Moreover, the blue section with the teeth on the outside concerning the bundle must bend stronger than the purple one with the teeth on the inside. Hence, it is achieved that they both touch the bundle in the right sequence automatically. This is important as the fixation mechanism of the teeth wouldn´t work if they were positioned the other way around. To achieve this, material of different flexibility might be used for the blue and the purple section.

In the end of phase 2, the clamping device is fixed to the bundle but neither stabilizes it nor brings up enough pressure upon it yet. This will be achieved in the next phase.

Figure 3.26 Product roughly adjusted to the bundle



Phase 3

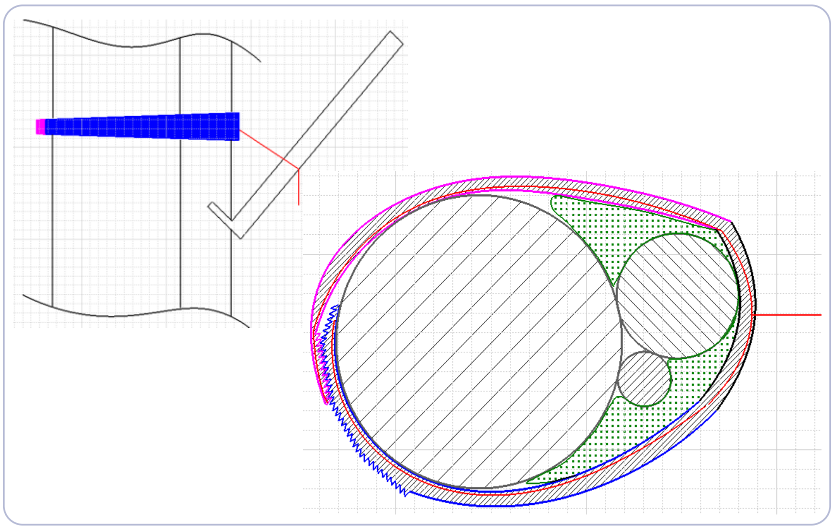
The former phase prepared the product for being completely fixed in this third phase. It already clings to the bundle autonomously. Thus, the user is now capable of gathering and positioning an additional mounting tool, which is necessary in order to bring up enough force for the last part of the activation of the fixation mechanism (Figure 3.27).

This tool might be a lever with a simple shape, which the user connects to the sinew and charges with force. By doing this, the sinew is set under tension and thus causes a further deformation of the casing, which increases the pressure on the bundle. As a consequence of this pressure, the components of the bundle can´t move relative to each other in vertical direction. Furthermore, the green adaption part reaches the maximum of possible deformation and is completely adapted to the bundle. Consequently, the small fragments transmit the pressure from the casing part to the bundle. Hence there is no more space for the bundle`s components to move horizontally and they are completely stabilized. The last act is to fixate the synthetic sinew in order to keep the tension. By doing this, the mounting act is completed.

In order to keep the vertical fixation of the bundle by pressure, it would also be helpful to choose a material for the inner blue and purple sections, which builds up high friction concerning the bundle´s components. However, the horizontal fixation also strongly depends on the green adaption part.

Concerning the material choice of the adaption part´s cover, it is to recognize that its flexibility in vertical direction must be limited to avoid strong escape of the small fragments out of the area between bundle and casing. This escape would decrease the number of fragments, which fill the gaps by adaption. Thus, the intended blocking of horizontal movements of the bundle´s components would be reduced.

Figure 3.27 Product is firmly fixed to the bundle



After the three phases described above, the product is completely mounted and now fulfils its product function to fix the bundle together. Nevertheless, this function can be disrupted by rocks, which are the greatest source of irritation in the process of lifting or letting the bundle down into the ground. The problem is that the product might get stuck to the rocks, which emerge from the sidewall of the hole. In this case, it is necessary to avoid damage of the product. This is achieved by the small movements of the fragments inside the green cover, which allow a momentary accommodation of the product to the rock. When the barrier is passed, the fragments can jump back in their previous place again.

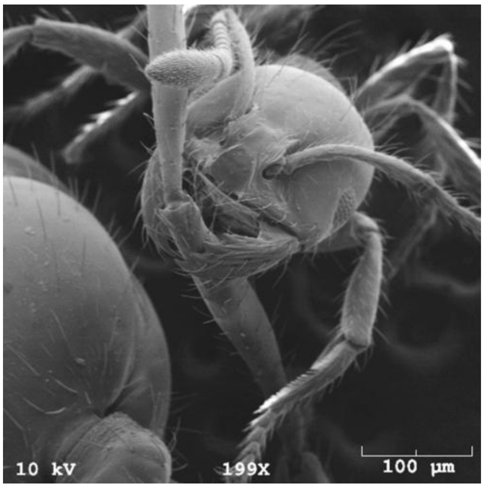
Therefore, it would be wise to choose a material for the small fragments, which possesses elastic characteristics. […]

3.5.3.3 The form

[…] *Ant raft in detail:* it is important to note that the water doesn´t play an important role and the fundamental parts are the ants and their legs, mandibles and rest of body.

In this more detailed view of the connection between the ants within the raft, the overall function is the attachment of the ants to each other. Therefore, the legs and mandibles have to get positioned closely to each other. The mandible of one is connected with the leg of another ant. For the purpose of holding together constantly, the legs and mandibles of the different ants are firmly attached to each other by closing the mandibles strongly. […]

Figure 3.28 Ant raft in detail – connected ants (Mlot, Tovey, & Hu, 2011)



Comparison the Figure 3.23 and the detailed view of the ant raft presented in Figure 3.28 the morphological similarities between the main NSoI and the BIP are obvious.

3.6 - Experiment Nr. 4

Due to the fact that Designer Nr. 3 (See Table 3.7 for the details) is the researcher that developed the Problem-Solving Methodology, which is acting as a designer/user, it has been asked to address two technical issues. The methodology in Experiment Nr. 4 has been applied to solve two separate technical problems. The former is about the development of a luggage rack for a bike sharing systems and the latter is about a retracting mechanism for the charging cable of electrical vehicles. The problem have been presented as test cases respectively in Table 3.4 and Table 3.5

PSSycle – Luggage Rack

Motivation: For a bike-sharing systems, where it is impossible foreseeing exactly the size, the dimension, and the number of the user's bags it is not possible to use a standard luggage rack. Through application of the Bio-Inspired Design, A non-standard luggage rack capable to allow bags of different types shall be designed.

Goals: Develop a Bio-Inspired *Conceptual* Solution for a luggage rack system through the implementation of Nature's solutions.

Visio.m – Retracting Cable Mechanism

Motivation: In the development of a new electric concept, car it has been faced the problem to choose the most appropriate retracting cable mechanism. Due to the innovativeness of the entire car, it has been decided to search for a new of retracting and collecting the cable in the car. Through application of the Bio-Inspired Design, one shall be designed.

Goals: Develop a new Bio-Inspired *Conceptual* Solution for the retracting cable mechanism through the implementation of Nature's solutions.

3.6.1 - Case Test C – The Technical Problem

In order to obtain a standard starting point to all the experiments according to (Pahl et al., 2007) it has been asked to the experts/customers to fulfil a standard questionnaire about the problem. In fact, the questionnaire with the answers of the experts has been given to the designer as a base to develop the requirements identification.

Questionnaire

1. **What are the objectives that the intended solution is expected to satisfy?**

    ✓ *Capacity to fasten different kinds of bags/luggage*
    ✓ *Capacity to transport more than one bag/luggage*

2. **What properties must it have?**

    - *Use of the available structures*
    - *Free access to the brake system*
    - *Free access to the transmission system*
    - *Possibility to adjust the seat for ergonomic reason*
    - *Simple use*
    - *Protection of the wiring system from theft*
    - *Min max weight*

3. **What properties must it not have?**

    - *Changes in the bike*
    - *Changes in the wiring system*
    - *Use of the seating space*
    - *Use of customized bags*

Figure 3.29 (left) the PSSycle prototype – (right) the nude bicycle used for the PSSycle project, the Homage hybrid light by Riese & Müller (http://en.r-m.de/bike/homage-hybrid-light)

The specifications about the dimension have been directly measured by the author on the prototype present in the lab at the Lehrstuhl für Produktentwicklung of the TUM Technische Universität München.

3.6.2 - The Problem Solving Process

Starting to the questionnaire, the pictures of the system and some meeting with the expert the requirements list has been developed and it is provided in the (Appendix A). The outputs of each step are reported in the following sub-sections.

3.6.2.1 Step 1: The Problem Definition

Starting from the requirements list the technical problem has been rewrite as follow:

- **NIST Action Verb formulation** (Connect, Couple, Join)
- **NIST Flow** (Material, Solid, Object)

3.6.2.2 Step 2: Reframing the Problem

Due to the application of the correlation matrix the correspondent class of Natural function is:

Biomimicry Taxonomy (Make, Physically Assemble, Structure)

3.6.2.3 Step 3: Natural Source of Inspiration Search

Starting from the above-mentioned class of Natural Functions the search for the NSoI has been performed. Due to the high number of sources of inspiration a set of criterion for the pre-selection has been developed:

a) Phenomenon's scale
b) Environmental conditions
c) Morphological Similarities
d) Physical mechanism realisation (most apparent ones)

Then the criterions have been compared using the rank order approach. The results are presented in Table 3.25

Table 3.25 Pairwise comparison of the evaluation criteria

Is more important than?	(a)	(b)	(c)	(d)	Sum
(a) Phenomenon's scale		1	1	1	**3**
(b) Environmental conditions	0		0	1	**1**
(c) Morphological Similarities	0	1		1	**2**
(d) Physical mechanism realisation (most apparent ones)	0	0	1		**1**

After the rank of the parameters, it has been necessary to also have a scale for the fulfilment of these criteria by the NSoI. For this purpose the Likert-type scale from (Vagias, 2006) has been adopted.

1. Absolutely inappropriate
2. Inappropriate
3. Slightly inappropriate
4. Neutral
5. Slightly appropriate
6. Appropriate
7. Absolutely appropriate

Thereby the level of appropriateness was weighted in values from 1 to 7. While 1 said that the specific NSoI was absolutely inappropriate concerning a criterion, 7 is the best grade and declared the NSoI as absolutely appropriate concerning the criterion.

Table 3.26 Pairwise comparison of the evaluation criteria

	Natural Source of Inspiration for BT Class: **Make/Physically assemble/Structure**	(a)	(b)	(c)	(d)	Sum
1	Structure and shape provide flexibility: vines	6	6	2	2	30
	…	…	…	…	…	…
13	Shapes cover curved surfaces efficiently: tortoise	5	6	6	4	37
	…	…	…	…	…	…
21	Leaf serves as container: red oak roller weevil	5	6	4	6	35
	…	…	…	…	…	…
24	Joints have two degrees of bending freedom: arthropods	4	6	5	4	32
25	Leaves resist gravitational loading: broad-leaved trees	5	4	4	3	30
	…	…	…	…	…	…
61	Capsid proteins self-assemble to form stable shell: virus	1	2	1	2	9

The NSoI that have been considered appropriate have reached a sum equal or bigger than 30

3.6.2.4 Step 4: Defining the Nature's Solutions

From the evaluation of the sixty-one descriptions available via the AskNature database under the matrix above, three NSoI have established themselves as the most relevant:

1. Shapes cover curved surfaces efficiently: tortoise
2. Leaf serves as container: red oak roller weevil
3. Joints have two degrees of bending freedom: arthropods

For each of the above-mentioned natural systems the designer has developed the functional-causal model (see Appendix E).

3.6.2.5 Step 5: The Principle Extraction

The process for extracting the crucial or applicable information of the inspiration sources and their models is based upon the guidelines proved within the Problem-Solving Methodology. This rule set deconstructs data into four distinct categories i.e. *Function, Behavior, Structure and Morphology*. In turn, specific design considerations are associated with each aspect through the research to aid in direction the implementation of the natural system in the final conceptual solution.

Table 3.27 Matrix of information extraction from the natural sources of inspiration

NSoI	Nature's solution	Category
Shapes cover curved surfaces efficiently: tortoise	**Shell**	Morphology
	Shell blocks	Shape & Arrangement
Leaf serves as container: red oak roller weevil	**Leaf folding**	Behaviour
Joints have two degrees of bending freedom: arthropods	**Joints**	Structure
	Folding	Function

3.6.2.6 Step 6: The Design Phase

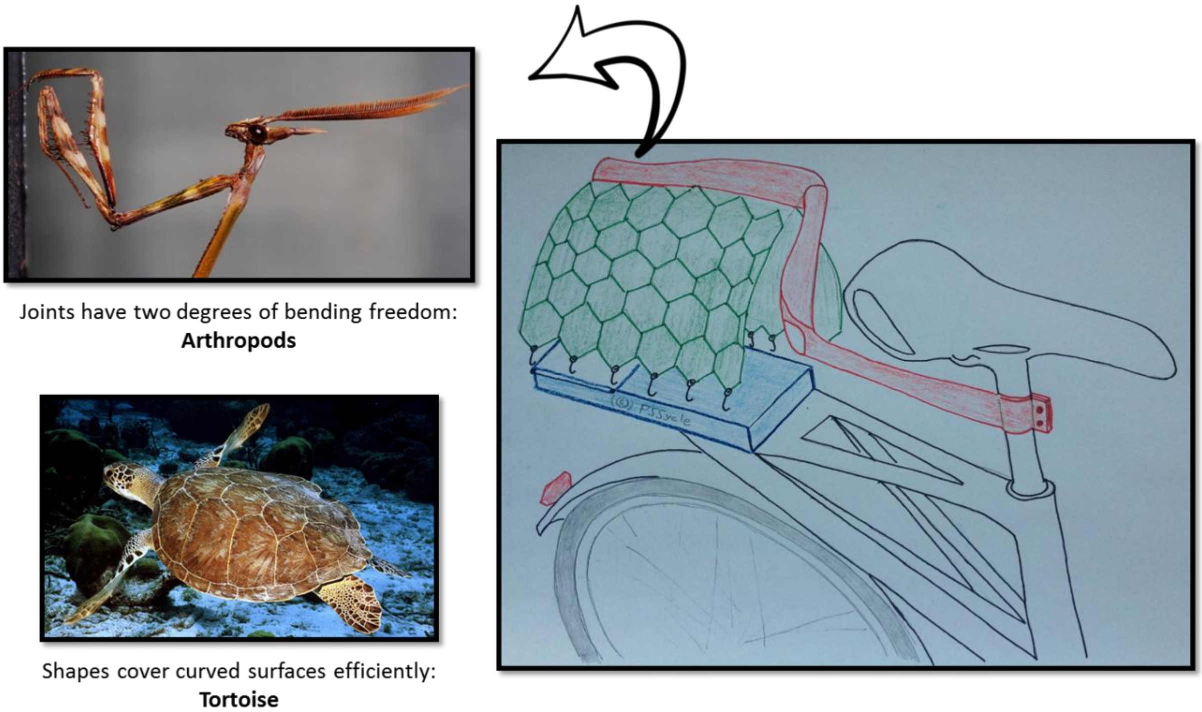
Upon completion of the extraction of Nature's solution information, the Bio-Inspired Conceptual Solution has been designed through the application and adaptation of function and mechanism from the NSoI.

3.6.3 - The Bio-Inspired Conceptual Solution

The standard luggage racks usually are baskets that contain the bags. Instead, the Bio-Inspired Conceptual Solution proposed works by creating a volume that spans from the top in order to contain the bags (See Figure 3.30).

The inspiration comes from the combination of three different NSoI. The first is the turtle, which gave the idea of creating a volume to contain the bags. Then the arthropods have shown the solution for the folding mechanism. Finally, the red oak roller weevils procure the solution for folding the nets that constitute the walls of the container.

Figure 3.30 Arthropods & Tortoise – Bio-Inspired Conceptual Solution of the Luggage Rack



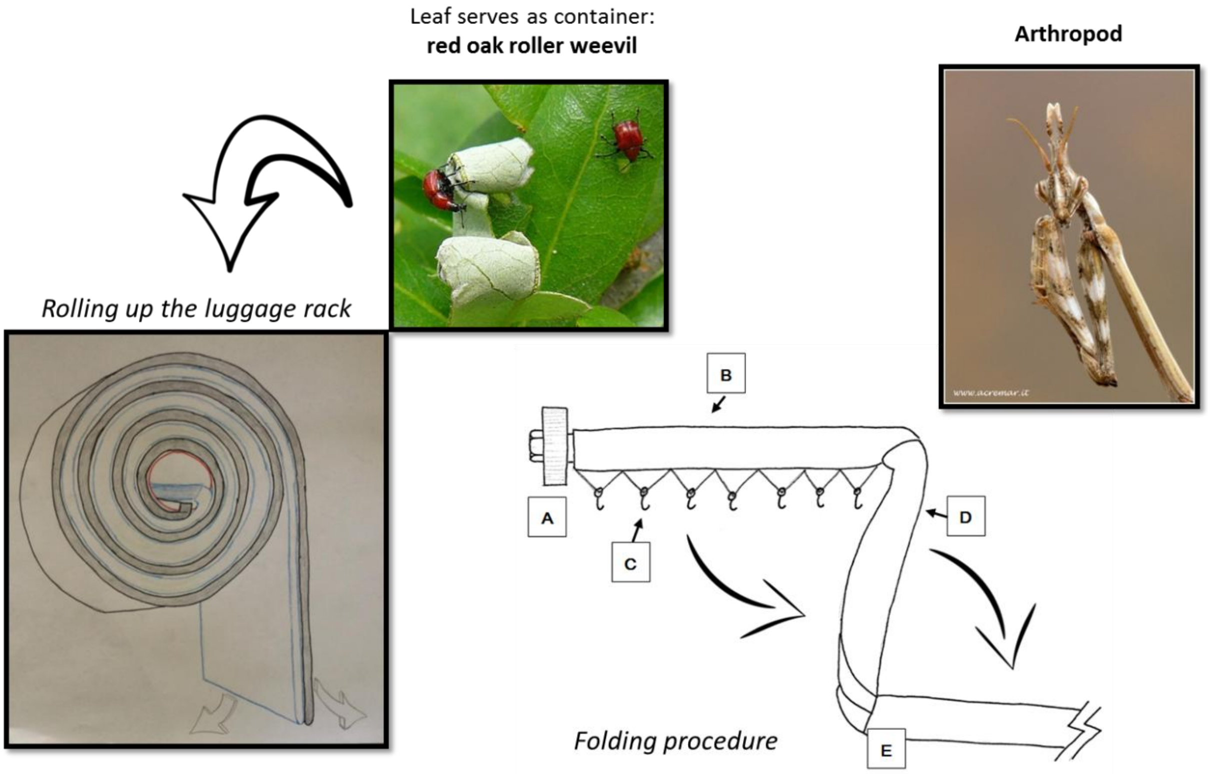
3.6.3.1 Approximate description of the technology

Due to the need of allowing and fix different bags' sizes and shapes and the presence of the electronic box of the bicycle that do not allow the application of a standard basket it has been necessary create a "cover" volume on the luggage rack surface. The reasons are multiple, for example, the electronic box of the electric-bike is constructed by a plastic material, which does not allow the use of screws on its surface, and because of the need of opening the electronic box in order to charge the batteries with an electric plug.

The volume can be created by the adoption of a system that mimics the arm of anthropoids that have two degree of freedom for each joint. This aspect allows that the upper part of the volume remains centred and produces the necessary constrain to do not allow the movements in the direction normal to the axis of the bike.

The system can be folded in order to be collected under the seat allowing the opening of the electronic-box. Moreover, to collect the elastic net that contains the bags a third source of inspiration has been taken by the work on a leaf of the red oak by the roller weevil. This animals rolls up in a double layer the leafs, so the same procedure have been transferred to the technical solution in order to collect the elastic net as it is shown in Figure 3.31.

Figure 3.31 Red oak roller Weevil, rolling up the Bio-Inspired Luggage Rack – Folding procedure



3.6.3.2 The working principle

The system is composed by the following components:

A. Handle
B. Elastic net case
C. Hooks
D. Structural bar
E. Seat bar connecting road

The handle [A] allows performing two operations in the system. First of all, it is used to create the tension to fix the luggage. Turning the handle in anticlockwise direction the net is tensioned and the case [B] is pushed on the luggage. Then pulling the handle it is possible to disarm the spring in order to allow the free movement of the net.

Inside the case [B] there is a mechanism that is provided by a spring with a small amount of force allows the net to be recalled automatically. The spring has to be dimensioned in order to do not require a big effort to extract it from the case in order to cover the bag.

Furthermore, on the right side of the mast used to roll up the net there is a mechanism that when reaches a certain level of tension allows to lock the net. The tension generated by the mechanism fixes the bag. This condition is reached due to the rotation of the handle and can be eliminated by pulling it. This operation allows extracting the bag from the luggage rack.

At the end of the net, a series of hooks [C] allows fixing it on the frame of the bicycle.

Between the case [B] and the structural bar [D] there is a joint that have two degree of freedom. These degrees of freedom permit the rotation of the case [B] respect to [D] in the plane that contains the frame of the bicycle. The rotation goes from complete closed i.e. [B] parallel to [D] to complete opened [B] at 90° respect to [D].An analogous folding process with the same angles of rotation is possible between [D] and [E].

When the net is completely rolled up inside [B] and both, [B] is parallel to [D], and [D] is parallel to [E], the system is in the closed configuration.

3.6.3.3 The form

The net [C] is made by a set of hexagons. In fact, the hexagons are characterized to have the bigger numbers of sides shared in plane figures. This property allows covering a surface using the smallest amount of rope for making the "building blocks".

The hooks [C] have to be dimensioned according to the size of the frame in order to allow the user to be able to fix them to the bicycle’s frame.

3.6.4 - Case Test D – The Technical Problem

In order to obtain a standard starting point to all the experiments according to (Pahl et al., 2007) it has been asked to the experts/customers to fulfil a standard questionnaire about the problem. In fact, the questionnaire with the answers of the experts has been given to the designer as a base to develop the requirements identification.

Questionnaire

1. **What are the objectives that the intended solution is expected to satisfy?**

   - ✓ *Capacity to connect the electrical vehicle to a standard house socket*
   - ✓ *Capacity to collect the cable on board of the car (cable winder)*

2. **What properties must it have?**

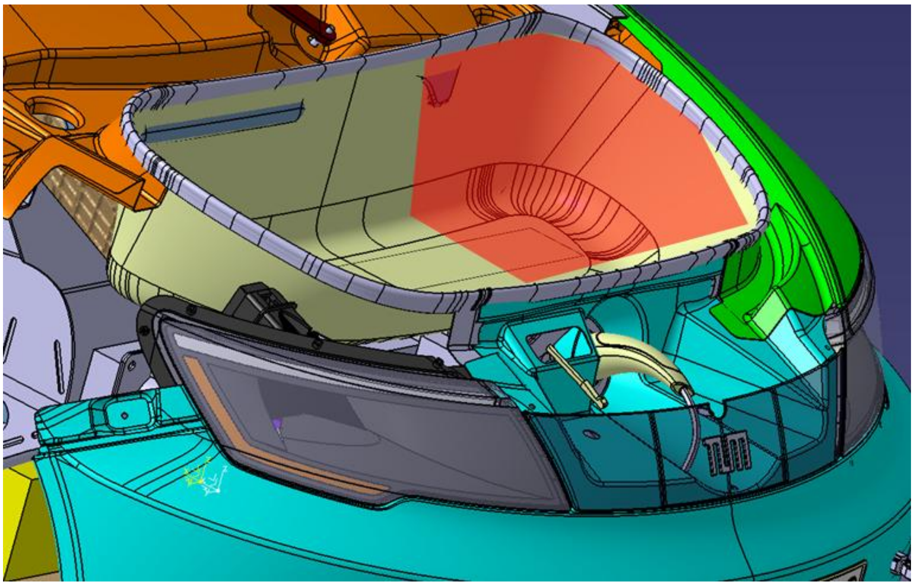
   - *Capacity to retract the charging cable*
   - *Capacity to connect to a standard house socket*
   - *Cable’s ability to be stretched when the car is charging*
   - *Users can access to the plug on the front and to the external socket lead*
   - *Min max space occupation*

3. **What properties must it not have?**

   - *The Retracting Cable Mechanism has not to be a standard solution of cable winder for household applications i.e. vacuum cleaner, hair dryer etc.*

Further details and dimensions have been obtained by regular meeting with the designers responsible for the project.

Figure 3.32 visio.m car trunk – in orange the volume dedicated to the Retracting Cable Mechanism



3.6.5 - The Problem Solving Process

Starting to the questionnaire, the pictures of the system and some meeting with the experts the requirements list has been developed and it is provided in the (Appendix A). The outputs of each step are reported in the following sub-sections.

3.6.5.1 Step 1: The Problem Definition

Starting from the requirements list the technical problem has been rewrite as follow:

- **NIST Action Verb formulation** (Control Magnitude, Change, Condition)
- **NIST Flow** (-, -, -)

It is important to note that in this problem such in the one faced in the test case B it has not been used the flow in the description of the problem using the correlation matrix.

3.6.5.2 Step 2: Reframing the Problem

Due to the application of the correlation matrix the correspondent class of Natural function is:

Biomimicry Taxonomy (Modify, Adapt/Optimize, Optimize Space/Martials)

3.6.5.3 Step 3: Natural Source of Inspiration Search

Starting from the above-mentioned class of Natural Functions the search for the NSoI has been performed. Due to the high number of sources of inspiration a set of criterion for the pre-selection has been developed:

e) Phenomenon's scale
f) Environmental conditions
g) Morphological Similarities
h) Physical mechanism realisation (most apparent ones)

Then the criterions have been compared using the rank order approach. The results are presented in Table 3.25

Table 3.28 Pairwise comparison of the evaluation criteria

Is more important than?	(a)	(b)	(c)	(d)	Sum
(a) Phenomenon's scale		1	1	1	**3**
(b) Environmental conditions	0		0	1	**1**
(c) Morphological Similarities	0	1		1	**2**
(d) Physical mechanism realisation (most apparent ones)	0	0	1		**1**

After the rank of the parameters, it has been necessary to also have a scale for the fulfilment of these criteria by the NSoI. For this purpose the Likert-type scale from (Vagias, 2006) has been adopted.

Table 3.29 Pairwise comparison of the evaluation criteria

	Natural Source of Inspiration for BT Class: **Modify-Adapt/Optimize - Optimize space/materials**	(a)	(b)	(c)	(d)	Sum
1	Shell is minimum free energy structure: viruses	4	4	6	6	34
	…	…	…	…	…	…
11	Large volumes move through small spaces: common earthworm	4	6	6	6	36
	…	…	…	…	…	…
38	Shell protects, supports, and allows for growth: shelled mollusks	4	6	6	6	36
	…	…	…	…	…	…
47	Beak size optimized for thermal regulation: birds	4	6	6	4	34
48	DNA densely packed without knots: humans	4	4	6	6	34
	…	…	…	…	…	…
56	Proteins share iron: Crocosphaera watsonii cyanobacteria	2	4	1	2	14

Thereby the level of appropriateness was weighted in values from 1 to 7. While 1 said that the specific NSoI was absolutely inappropriate concerning a criterion, 7 is the best grade and declared the NSoI as absolutely appropriate concerning the criterion.

The NSoI that have been considered appropriate have reached a sum equal or bigger than 34

3.6.5.4 Step 4: Defining the Nature's Solutions

From the evaluation of the sixty-one descriptions available via the AskNature database under the matrix above, three NSoI have established themselves as the most relevant:

1. Large volumes move through small spaces: common earthworm
2. Shell protects, supports, and allows for growth: shelled mollusks

For each of the above-mentioned natural systems the designer has developed the functional-causal model (see Appendix E).

3.6.5.5 Step 5: The Principle Extraction

The process for extracting the crucial or applicable information of the inspiration sources and their models is based upon the guidelines proved within the Problem-Solving Methodology. This rule set deconstructs data into four distinct categories i.e. *Function, Behavior, Structure and Morphology*. In turn, specific design considerations are associated with each aspect through the research to aid in direction the implementation of the natural system in the final conceptual solution.

Table 3.30 Matrix of information extraction from the natural sources of inspiration

NSoI	Nature's solution	Category
Large volumes move through small spaces: common earthworm	**Local size variation**	Function
Shell protects, supports, and allows for growth: shelled molluscs	**Axial growth**	Function
	Shell	Morphology

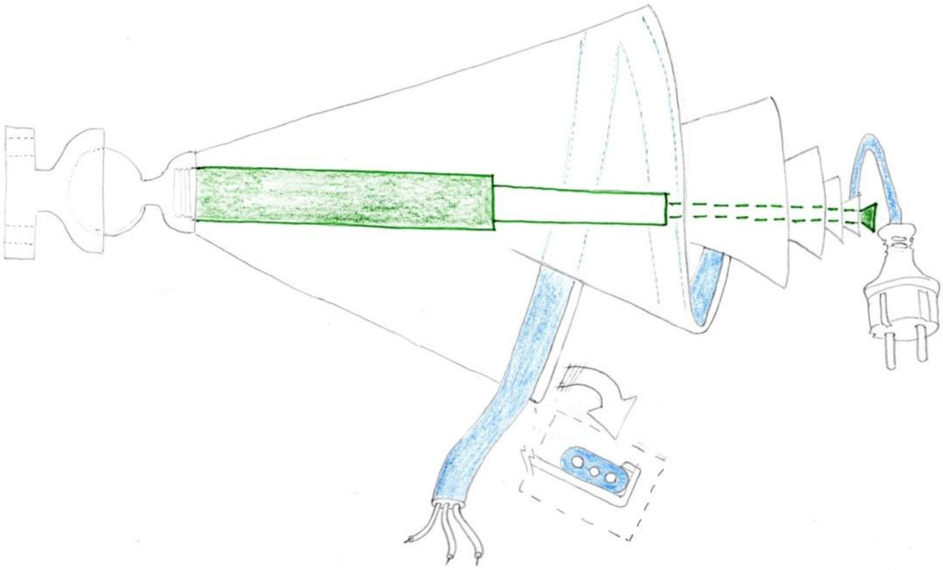
3.6.5.6 Step 6: The Design Phase

Upon completion of the extraction of Nature's solution information, the Bio-Inspired Conceptual Solution has been designed through the application and adaptation of function and mechanism from the NSoI.

3.6.6 - The Bio-Inspired Conceptual Solution

Figure 3.33 show an overall drawing of the Bio-Inspired Conceptual Solution developed for the Test Case D. Shells increase their size to allow the growth of the shellfish. Usually growth is radial respect to the axis of the shell itself. Among the others there is a specific type of shell that grows radially, respect to its axis. The growth direction of the Thatcheria Mirabilis is the feature that characterizes the Bio-Inspired Concept proposed for the Retracting Cable Mechanism for the visio.m project.

Figure 3.33 An overall drawing of the Bio-Inspired Retracting Cable Mechanism

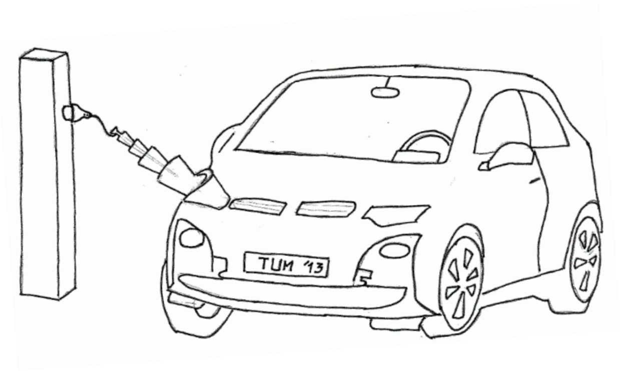


Due to the adoption of a standard electrical plug-in, the solution has the capacity to connect the electrical vehicle, during the charge period, to a standard house socket.

3.6.6.1 Approximate description of the technology

Figure 3.34 shows the RCM in the Open Configuration installed on the prototype. The RCM, due to its structure, allows the cable to be stretched and suspended from the ground when it is in the open configuration.

Figure 3.34 Access and connection to the electrical vehicle to a standard house socket



The users can access to the plug on the front part of the car. The extraction of the plug can be done after opening a cover, which protects the RCM. The flap protects the system from the dust, the water and the little animals that crash on the front part of the car during its motion and from the ice during winter period.

In the closed position (Figure 3.35), the RCM is able to collect the cable on board of the car (cable winder) and due to the fixation of the cable to the side of the shell (see the details in the zoom in Figure 3.33).

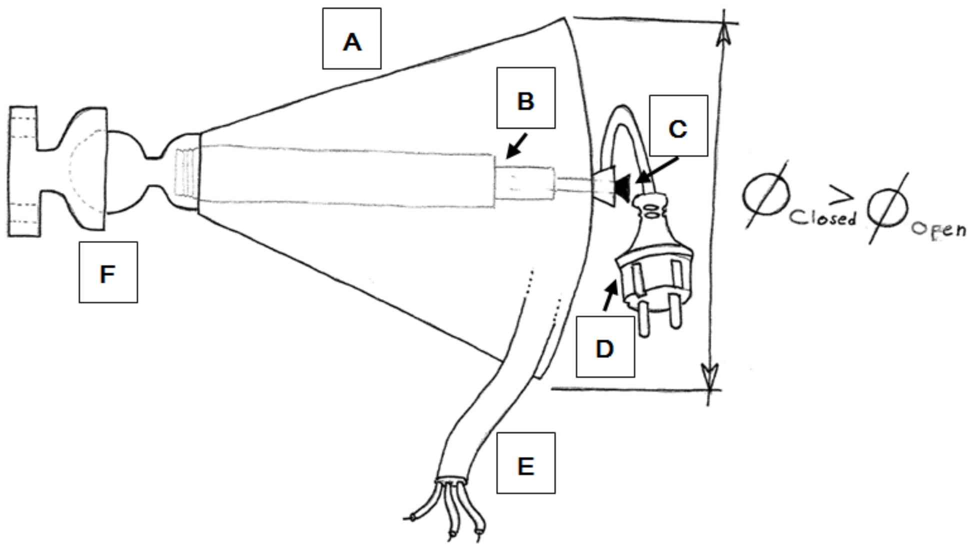
3.6.6.2 The working principle

The system is composed by the following components:

A. Shell spring
B. Telescopic mast
C. Handle
D. Cable
E. Standard plug-in
F. Spherical joint

The spring [A] is realized by means of elastic material, which allows the capability of the system to automatically recover the original shape in the closing position (Figure 3.35).

Figure 3.35 The Retracting Cable Mechanism in the Close Configuration

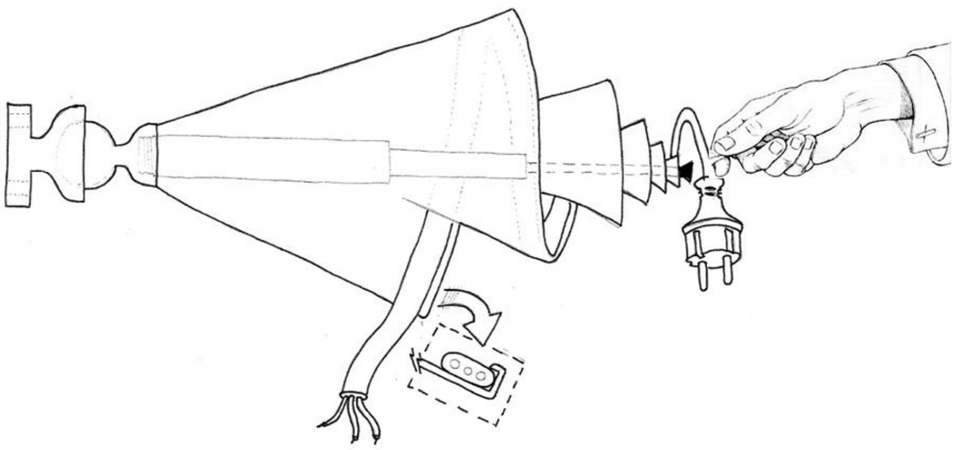


Pulling the handle [C] it is possible to change the configuration of the system from the closed position to the open position (Figure 3.36). The central telescopic mast [D] supports the entire RCM in the open position.

The RCM can be blocked in the open position due to a little turn of the handle [C] that allows the mast, by means of an internal blocking system, to maintain the configuration chosen by the user. Turning the handle [C] in the opposite direction the mast is unlocked allowing the system to move forward in order to restore the closed configuration.

It is important to note that the external diameter of the system in the closed configuration has an external dimension $Ø_{closed} < Ø_{open}$. That is a fundamental requirement because allow the functioning, in the open configuration, of the spherical joint [F]. The spherical joint allows the user to arrange the system on the most adequate direction in order to reach easily the wall socket.

Figure 3.36 The Retracting Cable Mechanism in the Open Configuration

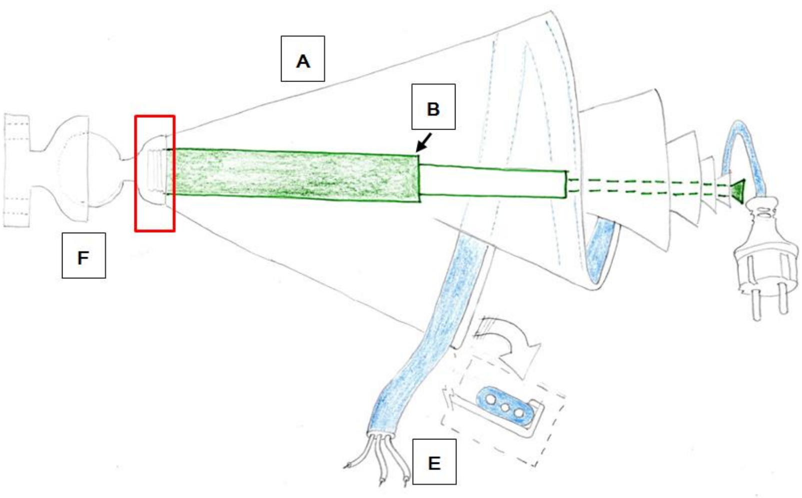


Finally, a further consideration about the difference of the diameter in the two configurations (open vs closed) is that in the closing position the $Ø_{closed}$ is the same of the hole in the frame of the vehicle, which allows the system to not move. On the other hand in the open configuration the $Ø_{open}$ is smaller of the hole diameter in the frame which allows the ability to direct the RCM due to the presence of the spherical joint.

3.6.6.3 The form

The spring [A] has the overall shape and the proportions of the Thatcheria Mirabilis. The proportions of growth are well known in the biological science. In the lower part of the shell (evidenced by a square in Figure 3.37) there is a flat plane, which has a hole. The hole allows the fillet of the telescopic mast [B] to be fixed on the spherical joint [F] and at the same time fixing rigidly the spring [A].

Figure 3.37 An overall drawing of the Bio-Inspired Retracting Cable Mechanism



The cable [E] as presented in the zoom in Figure 3.37 is flat. This shape allows rolling and fixing easily to the spring [A]. The way of fixing the cable can be a shape constrain, which allows both the cable to be fixed and to be protection from be pulled outside of the shell.

3.7 - Experiment Nr. 5

The last experiment conducted in this research is aimed at testing the parameters individuated by the three designers that have applied the entire methodology. The designers have chosen the parameters independently and freely when they faced the problem of reducing the number of the identified NSoI. In fact, the adopted search strategy leads to a number of NSoI too high. Due to this, the identification of a set of parameters to perform the pre-selection of the NSoI has been necessary.

The details about the participants to the experiment have been presented in Table 3.6 but it is important to remember that as explained in section 3.2 - they have a basic experience and some knowledge about the Problem-Solving Methodology and the relative tools.

During the experiment it has been asked to the designers to work on the problem that corresponds to the second solved by the Designer Nr. 3 and presented in Table 3.5

3.7.1 - The Task

In order to introduce the task to the designers it has been given a presentation structured as follows:

- Practical example
- Instruction to carry on task

As was done for Exercise Nr. 1, a standard file to compile with the result has been given to the participants.

In order to make a pre-selection of the NSoI it is necessary to define a set of criteria to evaluate them. A list of parameters has been given to the participants as an example:

- Environmental conditions
- Existence of a technical application of the Bio-Inspiration
- Morphological Similarity
- Phenomenon scale
- Technological feasibility
- Type of Natural System (e.g. plant, animal, cell etc.)
- **Other: Please specify**

Within the list there are also listed the parameters used by the designers in the methodology application but no indication have been given to the participants about this aspect. Furthermore, it is important to note that, the participants can define other parameters based on their design sensibility.

The experiment's procedure is the following:

1. Choose, among the parameters given as an example, the 3 or 4 you think that are the more relevant for the pre-selection of the NSoI
2. Rank the chosen parameters using the **Rank-order the list procedure** (See section 2.4.2.2)

The parameters selected during the experiment will be compared with the ones selected by the three designers in order to verify the following question:

- *Are the parameters chosen for the NSoI Pre-Selection robust?*

3.7.2 - The Results

Table 3.31 present the results obtained during Experiment Nr. 5

Table 3.31 List of parameters obtained as result of Experiment Nr. 5

Parameters	Count	Percentage
Morphological Similarities	7	26%
Phenomenon's scale	6	22%
Environmental conditions	4	15%
Technological Feasibility (Physical mechanism realisation)	4	15%
Existence of a technical application of the Bio-inspiration	2	7%
Costs	1	4%
Lower cost of realization	1	4%
Simplicity	1	4%
Type of Natural system	1	4%

Table 3.32 presents the results of the comparison between the parameters used for the pre-selection of the NSoI in the Experiments 2, 3 and 4 and the parameters obtained as a result in the Experiment Nr. 5

Table 3.32 Comparison between the parameters used for the pre-selection of the NSoI in the Experiments 2, 3 and 4 and the parameters obtained as a result in the Experiment Nr. 5

List of parameters *(in alphabetical order)*	Experiments Nr. 2,3 and 4	Experiment Nr. 5
Environmental conditions	☑	***15 %***
Existence of a technical application of the Bio-Inspiration		7 %
Morphological Similarity	☑	***26 %***
Other: Please specify		11 % (each ≤ 4%)
Phenomenon scale	☑	***22 %***
Technological feasibility	☑	***15 %***
Type of Natural System (e.g. plant, animal, cell etc.)		4 %

It is important to note that, the control group has selected all the parameters used by the designers during the experiment. In the class other, that represent the 11% of the total have been collected all the parameters that have a value ≤ 4%

3.7.3 - The Findings

Due to the need of validating the entire Problem-Solving methodology and not the single tools' use, it is worth to draw some conclusions separately respect to the methodology's validation procedure.

The *morphological similarity* is the parameters that have been selected by the bigger number of designers. That parameter allows to simply implementing a Nature's solution that have a coherent shape with the problem simplifying the design phase.

In the same direction is the choice of the Phenomenon's scale that ensures the Natural system is exposed to the same entity of forces and loads.

Moreover, the interests in the *environmental conditions* show that it is important for the designer individuating a Natural system that works in the same conditions respect to the technical one.

Each designer decided to insert a parameter in the field ***other*** so there is a great variability in the chose. This can be related to the fact that each designer has some ranking criteria in his/her mind which leads him/her to insert the "missed" most relevant parameter for the problem.

Finally, it is possible to say that the choice of the parameters for the pre-selection of the NSol is robust. Indeed, all the parameters proposed by the designers have been selected and all of them are characterized to a percentage of selection > 15%

4 - Methodology's Validation

As introduced in the previous sections, the methodology's validation has been obtained through to the combination of two separate approaches:

A. **Ability of the methodology to guide the generation of the Bio-Inspired Conceptual Solution**
B. **Fulfilment of the project requirements by the developed Bio-Inspired Conceptual Solution**

The **Validation approach A** has been obtained by modifying the strategy proposed by (Coelho & Versos, 2010) in order to validate technological industrial design concepts. In any case, this validation method lacks in rigour for the verification of the features of the Bio-Inspired Conceptual Solutions.

In order to overcome this limitation it has been integrated with the **Validation approach B** that is focused on the characteristics of the methodology's outputs, i.e. the Bio-Inspired Conceptual Solutions. This approach is the one adopted to validate the software's outputs by the IEEE (IEEE Standards Board, 1990).

4.1 - Ability of the methodology to guide the generation of the Bio-Inspired Conceptual Solution

It is important to remember that, the approach developed by (Coelho & Versos, 2010) has been specifically developed for the validation of methodologies for Bio-Inspired Design. Anyhow, it has been modified according to the doctoral research aim. In fact, it has been decided to focus the attention on the analysis of the methodology's features using the following set of criteria:

i. *Usability of the "Nature's Solution(s)" during the Design Phase*
ii. *Multiple requirements satisfaction approach*
iii. *Effectiveness of the methodology*

4.1.1 - Usability of the "Nature's Solution(s)" during the Design Phase

The Experiment Nr. 1 has shown the ability of the selected tools in allowing the target designers to individuate the correct class of Natural Functions. The proposed use of the database allows designers without Biological Knowledge of select the most appropriate class(es) of NSoI.

Moreover thanks to the Experiments Nr. 2, 3 and 4 it has been possible to show that all the designers have been able to represent properly the knowledge about the NSoI by using the SAPPhIRE-DANE integrated model. The NSoI's models have allowed to obtain a structured description of the Nature's solutions improving the quality of the Natural information available during the design phase. Furthermore, during their compilation the designers have increased the understanding of the natural systems. Thanks to the structured representation of the information relative to the Nature's solutions, which have allowed a simple use of the natural knowledge during the design phase, none examples of use of the NSoI *a posteriori* have been found.

4.1.2 - Multiple requirements satisfaction approach

Table 3.19, Table 3.23, Table 3.27, and Table 3.30 show the natural information, classified in clusters i.e. *Function*, *Behaviour*, *Structure*, and *Morphology*, which has been used during the solution of the technical problems and sub-problems proposed in the test cases.

Based on the results obtained in the Experiments Nr. 2, 3 and 4, the methodology allows designers in using a specific Nature's solution for each problem or sub-problem. In fact, in none of the proposed concepts there are trade-off solutions for conflicts between non-compatible requirements.

4.1.3 - Effectiveness of the methodology

Finally, it is fundamental to verify if the Problem-Solving approach is "convergent" on a Bio-Inspired Conceptual Solution in a finite and industrially acceptable time. This aspect has been verified in terms of "*effectiveness"* of the methodology.

Due to the limited number of applications, it is not possible to deduce an average time for the problem solving process. Can be noticed that the overall time is a function of the number of NSoI individuated and the length of the textual description proposed in AskNature.org that varies for each entry of the DB.

According to the results obtained in the experiment Nr. 5, the average number of NSoI analysed and evaluated per hour is around **55 [NSoI/h]**. This value is useful to foresee an overall time for the search phase.

Finally, the proposed problem solving methodology has shown a complete convergence in its solving capabilities. In fact, the four test cases selected randomly among the problems available, at the Institute of Product Development of the TUM between February and July 2013, have been completely solved in terms of both problems and sub-problems. The Nature's solutions that have been represented by means of the SAPPhIRE-DANE model have been combined and then implemented in a set of four correspondent BIPs.

4.2 - Fulfilment of the project requirements by the developed Bio-Inspired Conceptual Solution

In order to have a proof of compliance it has been decided to use the approach derived by the computer science. As aforementioned, the **Part B** of the validation procedure is focused on the evaluation of the features of the output of the methodology, i.e. the Bio-Inspired Conceptual Solutions. According to the

IEEE Standard Glossary of Software Engineering Terminology, and specifically considering the std. 610.12-1990, the validation is defined as follows:

Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled (IEEE Standards Board, 1990).

Table 4.1 Comparison of the methodology step's outputs among the Test Cases

	Test Cases			
	A	B	C	D
NIST (Action)	Signal, Sense, Detect	Connect, Couple, Link [1] Connect, Couple, Join [2]	Connect, Couple, Join	Control Magnitude, Change, Condition
NIST (Flow)	Material, Solid, Object		Material, Solid, Object	
BT	Process Information, Send Signal, Tactile	Move or stay put, Attach [1] Make, Physically assemble [2]	Make, Physically Assemble, Structure	Modify, Adapt/Optimize, Optimize Space/Martials
Nr. of NSol	15	147	61	56
Selected NSol	3	3 + 1[*]	3	2
Model items	6	7	5	3
Proposed BIPs	1	4	1	1
Developed BIPs	1	1	1	1

Even though at the moment the methodology is paper based, it is important to foresee a structured verification of the outputs' features.

It is worth noticing that for a technical problem the development of the requirements list according to a standard PDP gives an *objective evidence* for the validation procedure. The requirement lists, made during the clarification task, have allowed verifying if the Bio-Inspired Conceptual Solutions *have fulfilled the particular requirements*.

All the BIPs presented in the sections 3.4.3 -, 3.5.3 -, 3.6.3 -, and 3.6.6 - have fulfilled all the D (*Demands*) reported in the requirements list (Appendix A) developed during the task clarification phase.

Conclusions

This last section aims at recalling and reorganizing the main elements of this work in order to draw some conclusions based on the hypothesis and the research questions that have been faced during the research.

Summary of the Activities

In the State of the Art it has been analysed the use of Nature as a source of inspiration in research, in the consultancy activities, and in industry. Then, the attention has been moved on the analysis of the use of Nature’s solution for design purposes, focusing the attention on the industrial needs. In fact, it has been individuated that the industrial interest is growing and at the same time is growing the need of having a better understanding of the natural phenomena for the design tasks. Some examples, such as the Biomimetic tennis rackets by Dunlop Sport or other design examples such the ones proposed by the Airbus show the interest in using the Natural knowledge at a deeper level respect just the marketing purposes. In doing so, the companies interested in BID, need tools and methods that support the BID.

Once accepted the main hypothesis for the Bio-Inspired Design, which means that *Nature’s solutions can be a source of innovation in the product development process,* the following research questions have been proposed:

i. How a designer can be guided to use nature as a source of inspiration in order to solve technical problems?
ii. What is the industrial applicability of a method of Problem-Solving based on the use of the tools currently developed by the scientific community for the BID?
iii. How these tools can be integrated into the Product Development Process?

In fact, the aim of this research has been the integration of the correct BID tools into a Problem-Solving methodology that is usable by designers without Biological knowledge and that allows the systematic development of Bio-Inspired Products.

In order to achieve the research’s aim, in the second chapter has been presented a problem solving methodology based on the six steps approach presented in (Helms et al., 2009). Thanks to the fact that this study has been aimed at the understanding of the design activities faced by the designers during BID, a set of indications about the goal of each step have been given by the authors but none indications about how to carry out the steps has been given. This “criticism” is one of the reasons because this approach is not suitable for industrial purposes and implies a low level of use of BID in industry.

In order to reduce the gap between academic research and industry for the proposed methodology, in the thesis have been individuated the most appropriate tools to carry out each step. Moreover, a set of methods that allow properly applying the selected tools have been developed. At last, a set of guidelines derived both from the analysis of a sample of BIPs and from a survey at the biologists has been integrated in the methodology. The guidelines present in step 3 allow the designers to improve the models of the NSoI and the communication with the biologist whenever necessary. Moreover, the guidelines proposed for the step 4 help the designers in the selection of the most appropriate natural information to start with for the design phase.

In order to validate the methodology a set of five experiments have been carried out. These experiments can be sorted in two categories. The first one has been used for the validation of the tools and the second one has allowed validating the methodology itself. In fact, in order to validate the tools' use, a set of target designers have carried out the experiments. Then, for the methodology's validation, a set of four test cases have been used by two groups of designers. It is important to note that the designers that have applied the methodology appertain to the boundaries groups of the target designers i.e. the lower limit and the upper in terms of knowledge about the methodology and design experiences.

The test cases have been selected randomly among the technical problems available at the Institute of Product Development of the TUM (Lehrstuhl für Produktentwicklung – TUM Technische Universität München) in the period between February and July 2013. For each test case, starting from the requirements questionnaire, the requirements lists have been developed and the problems have been broken into sub-problems.

Subsequently, the application of the problem solving methodology has started. The first step requires that the problems and the sub-problems must be rewritten in NIST terms. Starting from problem described in NIST terms, the NIST-BT correlation matrix has been applied in order to obtain the reframe of the technical problem in Biological terms. The output of the NIST-BT correlation matrix is a class of Natural functions that correspondent via the Biomimicry Taxonomy at the given technical problem. The individuated class of Natural Functions has been used as an input to perform the search of the NSoI into the database of natural strategies AskNature.org. Once individuated the entire list of NSoI, a pre-selection of them has been made in order to reduce the number of NSoI to a selected list that allows the designer to realize the SAPPhIRE-DANE integrated causal-function models of each NSoI. At last, thanks to the application of the guidelines, has been individuated the most appropriate solution for each design problem in order to develop the Bio-Inspired Conceptual Solution in the design phase i.e. the last step of the methodology.

The methodology has hence been validated following two strategies: the first one is aimed at validating the ability of the methodology to guide the designer in the development of the solution and then the other one is based on the characteristics of the output of the methodology, i.e. the BIPs.

The methodology's features have been checked using the following set of criteria:

i. *Usability of the "Nature's Solution(s)" during the Design Phase*
ii. *Multiple requirements satisfaction approach*
iii. *Effectiveness of the methodology*

Finally, the characteristics of the BIPs have been verified thanks to the comparison with the requirements list obtained during the clarification task. Noteworthy, this step is not part of the methodology but is a standard step in the Product Development Process.

Achievement of the Objectives

All the objectives proposed as a goal of the present research have been achieved. First of all, it has been possible to individuate a set of tools from the BID research field in order to properly carry out all the steps of the proposed Problem-Solving methodology. Among the proposed tools, some of them have been simply selected or improved and others have been specifically developed for the methodology, such as the NIST-BT Correlation Matrix. In fact, the matrix allows translating the technical problem in biological terms. Doing so, is possible individuating the most appropriate class of Natural Functions in the AskNature.org database that allows creating a match between Nature's solutions and technical problems.

Actually, a fundamental aspect of the methodology is that no Biological knowledge is necessary in order to perform the BID. This result has been obtained by the use of the correlation matrix combined with the approach adopted to perform the search in the database. It is important to note that no knowledge about biological keywords or natural phenomena is needed to perform the search.

The tool has been validated through the experiment Nr. 1, which shows that the problem reframe in Biological terms is robust both in terms of tool’s application by the target designers and in terms of output quality.

Moreover, the biological information has been used during the design phase. The proposed SAPPhIRE-DANE integrated model has been used for all the test cases instead standard ones. The new model have allowed the designers both to individuate the correct natural information in order to solve the technical problems and to find a specific Nature’s solution to solve each sub-problems. Given the availability of the natural information, no compromise solutions have been individuated. With the extraction of the natural information represented in the items of the models, it has been possible to individuate a specific solution for each technical problem.

The methodology has been effective both in terms of time and in terms of number of Bio-Inspired Conceptual Solutions developed 4 out of 4. Furthermore, all the BIPs satisfy the requirements lists.

Furthermore, it is important to note that the methodology is able to solve:

- Problems with standard solutions
- Inventive problems

Finally, the method can be inserted in the standard Product Development Processes i.e. the (Pahl et al., 2007) and the (Ulrich & Eppinger, 2012) in order to systematically use nature as a source of inspiration.

Limits of the BID Problem-Solving Methodology

The methodology has shown some limitations with reference to two specific aspects. The first one is related to the users:

- The methodology is usable by designer with limited mental inertia
- The methodology needs a basic knowledge on functional and causal modelling

The second one is related to the search phase:

- The search can be done into a limited number of natural phenomena
- Are searchable only functional problems

A further specification is necessary. Even if it possible searching exclusively functional problems thanks to the use of the integrated SAPPhIRE-DANE model is it possible implementing not only the *Function* but also the *Behaviour*, the *Structure*, the *Parameters evolution etc.*

Potential Applications

With the aim of reducing the gap between academic research and industry, stringent constrains have been imposed to the methodology. In fact, it has to be suitable for designers with limited design experience and without biological knowledge. Furthermore, the methodology has to be adoptable by SMEs that usually have low budgets that imply:

- No possibility to hire BID consultants, or biologists, to solve using Nature technical problems
- Need to use free or low budget tools

The methodology at the moment does not present any economic costs because free tools have been selected both for the description of the problems and for the search phase.

Furthermore, the applicability in the SME is privileged because they have:

- Centred Product Development Processes
- Clear Design strategy
- Presence of an entrepreneur(s) that is(are) involved in the decision process

The application may be extended to the big enterprises that have the following characteristics:

- Presence of a local Product Development Process that allows to have higher freedom in the decision making in respect to the head quarter
- Availability of budget for non-standard design activities such as BID

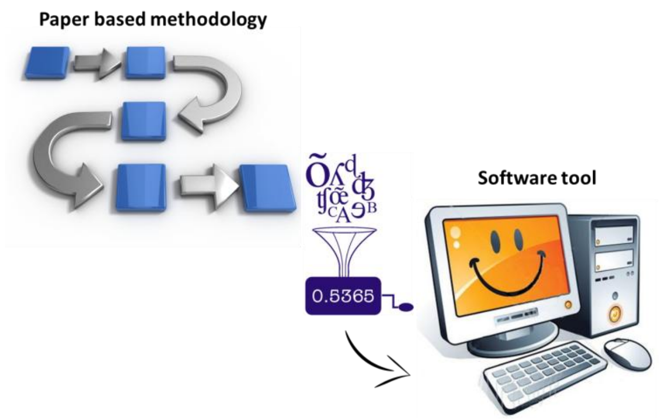
It is worth noticing that the application of the methodology is a function of the type of Product Development Process adopted in the industry/company and not of the dimension of it.

The fact that the search can be done into a limited number of natural phenomena it has been presented as a limitation. This limitation can be probably overcome soon. In fact the search for the NSoI can be extended to the entire web if the approach proposed by the (Vandevenne, Verhaegen, Dewulf, & Duflou, 2012) will be successful. They have proposed to use the Biomimicry Taxonomy to classify the results of the search of natural phenomena in the web for every type of source such as papers, web page (trustworthy), etc. This will increase dramatically the possibilities of the method if the search will be extended from a database of ≈2000 examples to the web.

On the other hand, this will create new problems and new challenges to the pre-selection of the NSoI list in order to reduce the results to an acceptable number

Further Developments

At the moment, the methodology is paper based and the most rational future development is the implementation of the methodology in an IT tool.



The software will have to be able:

- Supporting the NIST Problem description
- Reframing the technical problem in "biological terms" (NIST-BT correlation matrix)
- Searching into the Database of Natural strategies AskNature.org (or into the web)
- Supporting the creation of the NSoI functional/causal models
- Supporting the designer with guidelines for the concept development

This software tool will help the work of the designers and will speed-up the methodology's application time.

Furthermore, some improvements can be done also on the correlation matrix. In fact the level of overlap between the two taxonomies i.e. the NIST Functional Basis and the Biomimicry Taxonomy is not complete because the NIST is only about technical problems. For example in (Baldussu & Cascini, 2011) it is suggested to include into the NIST Functional Basis some specific biological flows in order to reach a better match between these two taxonomies and improve the possibilities of the problem reframe.

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Appendix A

A.1 – Requirements list Test Case: A

Table A.1 Requirements List – Test Case: A

USER		Requirements List Water Pump Retrieval System	D.o.I: 15.05.2013 Page: 1/1
Revision	**Priority**	**Requirement**	**Responsible**
		1) Geometry	
15.05.2013	D	Outer aperture diameter = 160 – 220 [mm]	J. Boyle
15.05.2013	D	Inner aperture diameter = 154 – 164 [mm]	J. Boyle
	D	Rope and wire compensation = 1 – 14 [mm]	
15.05.2013	D	Extrusion allowance = 10%	J. Boyle
		2) Kinematics	
	D	Horizontal clamping mechanism	
02.05.2013	W	Position and attachment feedback	A.R. Technology
	D	Flexible, self-adjusting clamping aperture	
		3) Forces	
15.05.2013	D	Weight of piping and water = 4.98×10^3 - 2.17×10^4 [kg]	J. Boyle
15.05.2013	D	Weight of pump = 30 – 170 [kg]	J. Boyle
		4) Energy	
	D	Pneumatic or electrical clamping mechanism	
		5) Material	
	D	Water resistant	
	D	Corrosion-resistant	
		6) Signals	
02.05.2013	W	Automatic clamping of mechanism	A.R. Technology
	D	Manual control from surface	
		7) Safety	
	D	Operator safety	
	D	Secure fixment to pipeline	
	D	Consideration of safety factors	
		8) Production	
	W	Full fabrication prior to arrival on-site	
		9) Assembly	
	W	Tool-free installation	
	W	Use existing mountings	
	D	No extensive foundations	
		10) Operation	
	D	Destination: Outdoor/Underground, high-moisture	
		9) Maintenance	
	D	'Bolt-on' components	
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A.2 – Requirements list Test Case: B

Table A.2 Requirements List – Test Case: B

A.R. Technology, Claudio Sutter		**Requirements list** Underwater pumping system tie problem		01/05/2013
Changes	**D/W**	**ID**	**Requirements**	**Responsible**
		1	**Geometry**	
01/05/2013	D	1.1	Minimum and max. length to hold the bundle: Minimum length: 146 [mm] Absolute maximum length: 344 [mm]	
	D	1.2	Adapts to standard size of users hand	
	D	1.3	Broad enough to deliver the necessary clamping force	
	D	1.4	Geometry which does not easily hook on stones	
	W	1.5	Self-explaining geometry for intuitive handling	
		2	**Kinematics**	
	D	2.1	Prevent relative movement of tube, rope etc.	
	W	2.2	Very few relative movement of the fixation product itself	
		3	**Forces**	
	D	3.1	Not to high force for fixing necessary (easy going movements)	
	D	3.2	Force on tube, ropes etc. must be limited automatically	
16.04.2013	D	3.3	Sufficient fixation force for creating stiffness and prevent movement between product and bundle and between rope and other cables (if there is not enough friction, the whole system cannot be pulled out of the hole properly)	C. Sutter
		4	**Energy**	
	W	4.1 =3.1	Mounting must be possible without tools -> without other energy than provided by the user	
		5	**Material**	
	D	5.1	Without splinters or sharp edges-> no danger for user of being hurt	
	D	5.2	No reaction with water. No disintegration in water	
16.04.2013	D	5.3	Prevent from breaking when deforming (e.g. by hooking stones) and deliver fixation force after deforming again	C. Sutter
	D	5.4	Temperature range -> no high changes of characteristics	
	D	5.5	Material must last about xx h	
		7	**Ergonomics**	
		7.1 = 1.2		
		7.2 = 3.1		
		8	**Operation**	
	W	8.1	Good cognition. If different lengths necessary -> different colours	
		9	**Maintenance**	
16.04.2013	D	9.1	Fixation mechanism must be manipulated to loosen it; or product must be destroyed without harming the tube etc.	C. Sutter
	W	9.2	Can be used more than one time	

		10	**Costs**	
	D	10.1	Low costs in development, production and material	
		11	**Schedule**	
	D	11.1	Concept finished and Bio-Inspired Design method tested until end of July	
REPLACES ISSUE OF 16.04.2013				

A.3 – Requirements list Test Case: C

Table A.3 Requirements List – Test Case: C

USER		Requirements List PSSycle Luggage Rack	D.o.I: 03.04.2013 Page: 1/1
Revision	**D/W**	**Requirement**	**Responsible**
		1) Geometry	
	D	Upper Electronic Box Base L = 18 [cm] – W = 40 [cm] c.a. 720 [cm²]	
	D	Electronic Box Side H = 6.5 [cm] – W = 40 [cm]	
	D	Electronic Box Flap L = 18 [cm] – W = 13 [cm] c.a. 325 [cm²]	
	D	Bicycle Side Interface L = 55 [cm] – H = 40 [cm] c.a. 825 [cm²]	A. Baldussu
		3) Forces	
	D	Luggage weight	R. Orawski
		4) Energy	
	D	Pneumatic or electrical clamping mechanism	
		5) Material	
	D	Electronic Box made of ABS	A. Baldussu
		6) Signals	
	W	Signal when you forget your luggage in the bike	R. Orawski
		8) Ergonomics	
	D	Possibility to adjust the seat for ergonomic reason	
	W	Protection of the wiring system from theft	
New Req.	D	Possibility to open the retracting-cable slot during charge	PSSycle Designers
	D	Simple use	
		10) Quality Control	
	W	Life time	R. Orawski
		10) Operation	
	D	Different types of bags: backpack, shopping bag or laptop bag	R. Orawski
		14) Maintenance	
	D	Free access to the brake system	R. Orawski
	D	Free access to the transmission system	R. Orawski
	D	Easy repair in case of damage	R. Orawski
REPLACES ISSUE OF 21.03.2013			

A.4 – Requirements list Test Case: D

Table A.4 Requirements List – Test Case: D

USER		Requirements List Retracting Cable Mechanism	D.o.I: 15.03.2013 Page: 1/1
Revision	**D/W**	**Requirement**	**Responsible**
		1) Geometry	
	D	In the front area under the front flap V = 10.000 [cm³]	
	D	Cable length L = 4 [m]	
		2) Kinematics	
	D	Capacity to retract the charging cable	D. Schmidt
	W	Cable's ability to be stretched when the car is charging	D. Schmidt
		4) Energy	
	D	High power (3.7 kW, max. Performance Schuko sockets)	
	D	Standard electrical net connection 220 [V] – 50 [Hz]	U. A. Reik
		5) Material	
	D	Long duration, without the cable to be possibilities of cooling	D. Schmidt
	D	Three-core cable	
	D	The plug has to be weatherproof	D. Schmidt
		8) Ergonomics	
W → D	D	Prevent the operator's hand burn	D. Schmidt
	D	Users can access to the plug on the front and to the external socket lead	
		13) Operation	
	D	Cable is cleaned / dried before it enters into the drying region	D. Schmidt
REPLACES ISSUE OF 14.02.2013			

Appendix B

B.1 – Functional basis reconciled function set

Table B.1 Functional basis reconciled function set (Hirtz et al., 2002a)

Function			
Class			Correspondent
Primary	*Secondary*	*Tertiary*	
Branch	Separate		*Isolate, sever, disjoin*
		Divide	*Detach, isolate, release, sort, split, disconnect, subtract*
		Extract	*Refine, filter, purify, percolate, strain, clear*
		Remove	*Cut, drill, lathe, polish, sand*
	Distribute		*Diffuse, dispel, disperse, dissipate, diverge, scatter*
Channel	Import		*Form entrance, allow, input, capture*
	Export		*Dispose, eject, emit, empty, remove, destroy, eliminate*
	Transfer		*Carry, deliver*
		Transport	*Advance, lift, move*
		Transmit	*Conduct, convey*
	Guide		*Direct, shift, steer, straighten, switch*
		Translate	*Move, relocate*
		Rotate	*Spin, turn*
		Allow DOF	*Constrain, unfasten, unlock*
Connect	Couple		*Associate, connect*
		Join	*Assemble, fasten*
		Link	*Attach*
	Mix		*Add, blend, coalesce, combine, pack*
Control Magnitude	Actuate		*Enable, initiate, start, turn-on*
	Regulate		*Control, equalize, limit, maintain*
		Increase	*Allow, open*
		Decrease	*Close, delay, interrupt*
	Change		*Adjust, modulate, clear, demodulate, invert, normalize, rectify, reset, scale, vary, modify*
		Increment	*Amplify, enhance, magnify, multiply*
		Decrement	*Attenuate, dampen, reduce*
		Shape	*Compact, compress, crush, pierce, deform, form*
		Condition	*Prepare, adapt, treat*
	Stop		*End, halt, pause, interrupt, restrain*
		Prevent	*Disable, turn-off*
		Inhibit	*Shield, insulate, protect, resist*
Convert	Convert		*Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, process, solidify, transform*
Provision	Store		*Accumulate*
		Contain	*Capture, enclose*
		Collect	*Absorb, consume, fill, reserve*

	Supply		*Provide, replenish, retrieve*
Signal	Sense		*Feel, determine*
		Detect	*Discern, perceive, recognize*
		Measure	*Identify, locate*
	Indicate		*Announce, show, denote, record, register*
		Track	*Mark, time*
		Display	*Emit, expose, select*
	Process		*Compare, calculate, check*
Support	Stabile		*Steady*
	Secure		*Constrain, hold, place, fix*
	Position		*Align, locate, orient*
Overall increasing degree of specification ->			

B.2 – Functional basis reconciled flow set & Power conjugate complements for the energy class of flows

Table B.2 Functional basis reconciled flow set & Power conjugate complements for the energy class of flows (Hirtz et al., 2002a)

Flow					
	Class		Correspondent		
Primary	*Secondary*	*Tertiary*			
Material	Human		*Hand, foot, head*		
	Gas		*Homogeneous*		
	Liquid		*Incompressible, Compressible, Homogeneous*		
	Solid	Object	*Rigid-Body, Elastic-Body, Widget*		
		Particulate			
		Composite			
	Plasma				
	Mixture	Gas-Gas			
		Liquid-Liquid	*Aggregate*		
		Solid-Solid			
		Liquid-Gas			
		Solid-Gas			
		Solid-Liquid-Gas			
		Colloidal	*Aerosol*		
Signal	Status	Auditory	*Tone, Word*		
		Olfactory			
		Tactile	*Temperature, Pressure, Roughness*		
		Taste			
		Visual			
	Control	Analog	*Oscillatory*	Power conjugate complements	
		Discrete	*Binary*	Effort analogy	Flow Analogy
Energy				Effort	Flow
	Human			Force	Velocity
	Acoustic			Pressure	Particle velocity
	Biological			Pressure	Volumetric flow
	Chemical			Affinity	Reaction rate
	Electrical			Electromotive force	Current
	Electromagnetical			Effort	Flow
		Optical		Intensity	Velocity
		Solar		Intensity	Velocity
	Hydraulic			Pressure	Volumetric flow
	Magnetic			Magnetomotiv force	Magnetic flux rate
	Mechanical			Effort	Flow
		Rotational		Torque	Angular velocity
		Translational		Force	Linear Velocity

	Pneumatic	Pressure	Mass flow
	Radioactive/Nuclear	Intensity	Decay rate
	Thermal	Temperature	Heat flow
Overall increasing degree of specification ->			

Appendix C – The Biomimicry Taxonomy

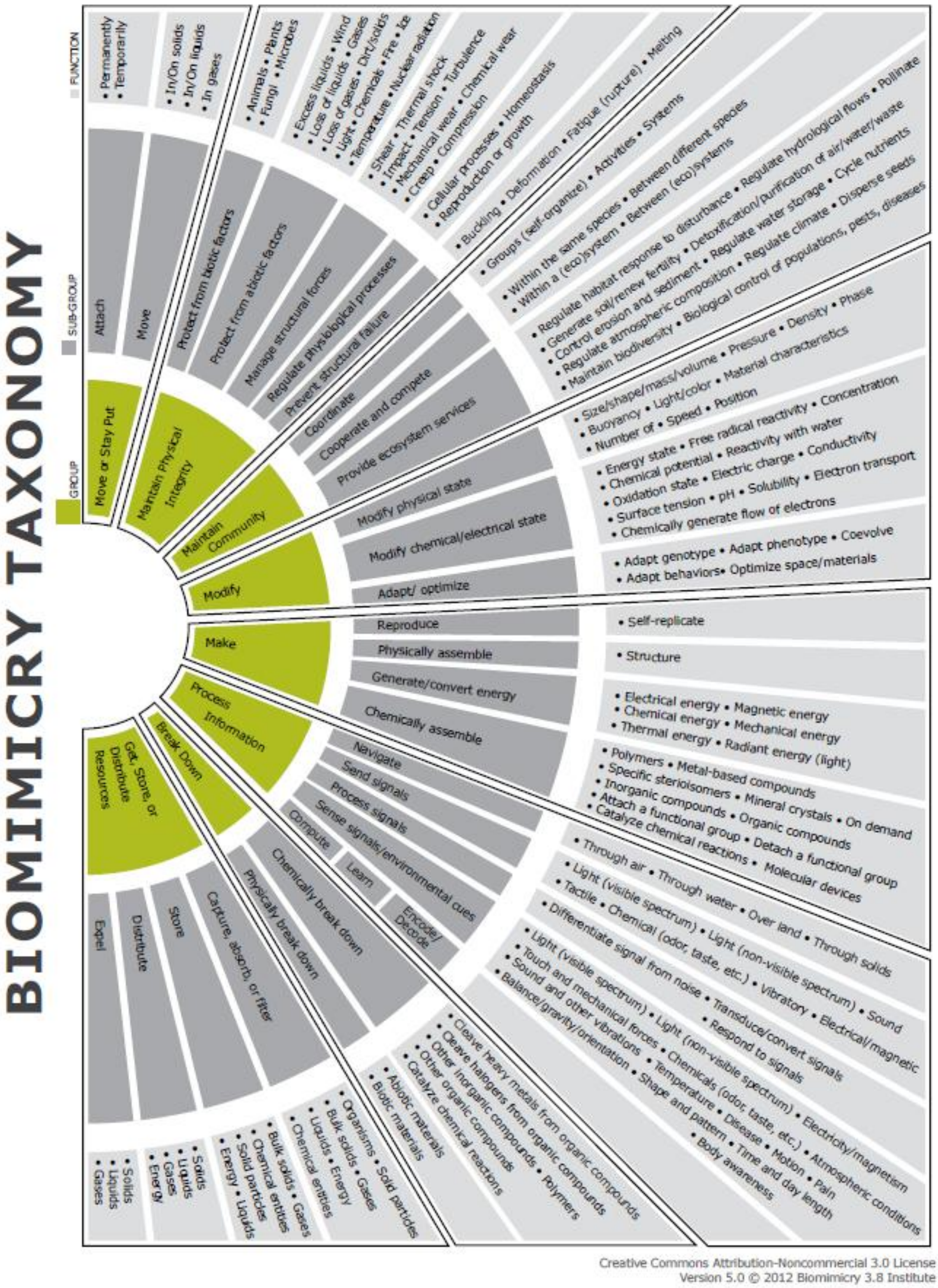


Figure C.1 The Biomimicry Taxonomy
(http://www.biomimicryinstitute.org/images//biomimicry_taxonomy.pdf)

Appendix D

D.1 – The correlation matrix NIST(Action)-BT

Table D.1 The correlation matrix NIST(Action)-BT

Biomimicry Taxonomy			NIST Functional Basis (Action)		
Group	Sub-Group	Function	Primary	Secondary	Tertiary
Move or Stay Put	Attach	*Permanently*	*Connect*	*Couple*	*Link*
		Temporarily			
	Move	*In gases*	*Channel*	*Transfer*	*Transport*
		In/On Liquid			
		In/On Solid			
Maintaining Physical Integrity	Protect from Biotic Factors	*Animals*	*Control Magnitude*	*Stop*	*Inhibit*
		Fungi			
		Microbes			
		Plants			
	Protect from Abiotic Factors	*Chemical Toxins*	*Control Magnitude*	*Stop*	*Inhibit*
		Dirt/Solid			
		Excess Liquid			
		Fire			
		Gases			
		Ice			
		Light			
		Loss of gasses			
		Loss of liquid			
		Nuclear Radiation			
		Temperature			
		Wind			
	Manage Structural Forces	*Chemical Wear*	*Control Magnitude*	*Stop*	*Prevent/Inhibit*
		Compression			
		Creep			
		Impact			
		Mechanical Wear			
		Shear			
		Tension			
		Thermal Shock			
		Turbulence			
	Regulate Physiological Processes	*Cellular Processes*	*Control Magnitude*	*Regulate*	*Increase/Decrease*
		Homeostasis			
		Reproducing or Growth			

	Prevent Structural Failure	*Buckling*	*Control Magnitude*	*Stop*	*Prevent*
		Deformation			
		Fatigue			
		Fracture (rupture)			
		Melting			
Maintain Community	Coordinate	*Activities*			
		Groups (Self-Organize)			
		Systems			
	Cooperate and Compete	*Between (eco)System*			
		Between different species			
		Within a (eco)System			
		Within the same species			
	Provide Ecosystem services	*Biological control of populations, pets, disease*	*Provision*	*Supply*	
		Control erosion and sediment			
		Cycle nutrients			
		Detoxification/purification of air/water/waste			
		Disperse seeds			
		Generate soil/renew fertility			
		Maintain biodiversity			
		Pollinate			
		Regulate atmospheric composition			
		Regulate climate			
		Regulate habitat response to disturbance			
		Regulate hydrological flows			
		Regulate water storage			

Modify	Modify physical state	*Buoyancy*	*Control Magnitude*	*Change*	*Increment, Decrement, Shape, Condition*
		Density			
		Light/colour			
		Material Characteristics			
		Number of			
		Phase			
		Position			
		Pressure			
		Size/shape/mass/volume			
		Speed			
	Modify chemical/electrical state	*Chemical Potential*	*Control Magnitude*	*Change*	*Increment, Decrement, Shape, Condition*
		Chemically generate flow of electrons (redox)			
		Concentration			
		Conductivity			
		Electric Charge			
		Electron Transport			
		Energy state			
		Free radical reactivity			
		Oxidation State			
		pH			
		Reactivity with water			
		Solubility			
		Surface Tension			
	Adapt/Optimize	*Adapt behaviours*	*Control Magnitude*	*Change*	*Condition*
		Adapt genotype			
		Adapt phenotype			
		Coevolve			
		Optimize space/materials			
Make	Reproduce	*Self-replicate*			
	Physically assemble	*Structure*	*Connect*	*Couple*	*Join*
	Generate/convert energy	*Chemical energy*	*Convert*		
		Electrical energy			
		Magnetic energy			
		Mechanical energy			
		Radiant energy (light)			
		Thermal energy			
	Chemical	*Attach a functional group*	*Connect*	*Mix*	

	assemble	*Catalyse chemical reactions*			
		Detach a functional group			
		Inorganic compounds			
		Metal-based compounds			
		Mineral crystals			
		Molecular devices			
		On demand			
		Organic compounds			
		Polymers			
		Specific stereoisomers			
Process Information	Navigate	*Over land*	*Channel/Signal*	*Transfer/Sense*	*(-) / Measure*
		Through solids			
		Through water			
		Through air			
	Process Signals	*Differentiate signal from noise*	*Signal*	*Process*	
		Respond to signals			
		Transduce/convert signal			
	Send Signal	*Chemical (odour, taste, etc.)*	*Signal*	*Indicate*	*Display*
		Electrical/Magnetic			
		Light-non-visible spectrum			
		Light-visible spectrum			
		Sound			
		Tactile			
		Vibratory			
	Sense Signal/Environment cues	*Atmospheric conditions*	*Signal*	*Sense*	*Detect/Measure*
		Balance/gravity/orientation			
		Body awareness			
		Chemical (odour, taste, etc.)			
		Disease			
		Light (non-visible spectrum)			
		Light (visible spectrum)			
		Motion			
		Pain			
		Shape and pattern			
		Sound			
		Sound and other vibrations			
		Tactile			
		Temperature			
		Time and day length			

	Compute		*Signal*	*Process*	
	Learn				
	Encode/Decode		*Convert*		
Break Down	Chemically break down	*Catalyse chemical reactions*	*Branch*	*Separate*	*Divide*
		Cleave halogens from organic compounds			
		Cleave heavy metals from organic compounds			
		Other inorganic compounds			
		Other organic compounds			
		Polymers			
	Physically break down	*Abiotic materials*	*Branch*	*Separate*	*Divide*
		Biotic materials			
Get, Store, or Distribute Resources	Capture, absorb, or filter	*Bulk solids*	*Provision/Branch*	*Store/Separate*	*Collect/Extract*
		Chemical entities			
		Energy			
		Gases			
		Liquid			
		Organism			
		Solid particles			
	Store	*Bulk solids*	*Provision*	*Store*	
		Chemical entities			
		Energy			
		Gases			
		Liquids			
		Solid particles			
	Distribute	*Energy*	*Branch*	*Distribute*	
		Gases			
		Liquids			
		Solids			
	Expel	*Gases*	*Channel*	*Export*	
		Liquids			
		Solid			

D.2 – The correlation matrix NIST-BT

Table D.2 The correlation matrix NIST-BT

Biomimicry Taxonomy			NIST Functional Basis					
			Action			Flow		
Group	Sub-Group	Function	Primary	Secondary	Tertiary	Primary	Secondary	Tertiary
Move or Stay Put	Attach	*Permanently*	*Connect*	*Couple*	*Link*			
		Temporarily						
	Move	*In gases*	*Channel*	*Transfer*	*Transport*			
		In/On Liquid						
		In/On Solid						
Maintaining Physical Integrity	Protect from Biotic Factors	*Animals*	*Control Magnitude*	*Stop*	*Inhibit*	*Material*	*Solid*	
		Fungi						
		Microbes						
		Plants						
	Protect from Abiotic Factors	*Chemical Toxins*	*Control Magnitude*	*Stop*	*Inhibit*	*Material*	*Solid*	
		Dirt/Solid					*Solid*	
		Excess Liquid					*Liquid*	
		Fire						
		Gases				*Material*	*Gas*	
		Ice					*Solid*	
		Light				*Energy*	*Electromagnetical*	*Optical*
		Loss of gasses				*Material*	*Gas*	
		Loss of liquid					*Liquid*	
		Nuclear Radiation				*Energy*	*Radioactive/Nuclear*	
		Temperature					*Thermal*	
		Wind					*Pneumatic*	
	Manage Structural Forces	*Chemical Wear*	*Control Magnitude*	*Stop*	*Prevent/Inhibit*			
		Compression						
		Creep						
		Impact						
		Mechanical Wear						
		Shear						
		Tension						
		Thermal Shock						
		Turbulence						
	Regulate Physiological Processes	*Cellular Processes*	*Control Magnitude*	*Regulate*	*Increase/Decrease*			
		Homeostasis						
		Reproducing or Growth						
	Prevent Structural Failure	*Buckling*	*Control Magnitude*	*Stop*	*Prevent*			
		Deformation						

		Fatigue						
		Fracture (rupture)						
		Melting						
		Activities						
	Coordinate	*Groups (Self-Organize)*						
		Systems						
		Between (eco)System						
	Cooperate and Compete	*Between different species*						
		Within a (eco)System						
		Within the same species						
		Biological control of populations, pets, disease						
		Control erosion and sediment						
Maintain Community		*Cycle nutrients*				*Material*	*Solid*	
		Detoxification/purification of air/water/waste						
		Disperse seeds						
		Generate soil/renew fertility				*Material*	*Mixture*	
	Provide Ecosystem services	*Maintain biodiversity*	*Provision*	*Supply*				
		Pollinate						
		Regulate atmospheric composition						
		Regulate climate						
		Regulate habitat response to disturbance						
		Regulate hydrological flows						
		Regulate water storage						
		Buoyancy						
		Density						
		Light/colour						
		Material Characteristics						
		Number of						
	Modify physical state	*Phase*	*Control Magnitude*	*Change*	*Increment, Decrement, Shape, Condition*			
		Position						
		Pressure						
		Size/shape/mass/volume						
Modify		*Speed*						
		Chemical Potential						
		Chemically generate flow of electrons (redox)						
		Concentration						
		Conductivity						
	Modify chemical/electrical state	*Electric Charge*	*Control Magnitude*	*Change*	*Increment, Decrement, Shape, Condition*			
		Electron Transport						
		Energy state						
		Free radical reactivity						
		Oxidation State						

		pH						
		Reactivity with water						
		Solubility						
		Surface Tension						
		Adapt behaviours						
		Adapt genotype						
	Adapt/Optimize	*Adapt phenotype*	***Control Magnitude***	***Change***	***Condition***			
		Coevolve						
		Optimize space/materials						
	Reproduce	*Self-replicate*						
	Physically assemble	*Structure*	***Connect***	***Couple***	***Join***			
		Chemical energy						
		Electrical energy						
	Generate/convert energy	*Magnetic energy*	***Convert***					
		Mechanical energy						
		Radiant energy (light)						
		Thermal energy						
		Attach a functional group						
Make		*Catalyse chemical reactions*				***Energy***	***Chemical***	
		Detach a functional group						
		Inorganic compounds						
		Metal-based compounds						
	Chemical assemble	*Mineral crystals*	***Connect***	***Mix***				
		Molecular devices						
		On demand						
		Organic compounds						
		Polymers						
		Specific stereoisomers						
		Over land						
	Navigate	*Through solids*	***Channel/Signal***	***Transfer/Sense***	***(-) / Measure***			
		Through water						
		Through air						
		Differentiate signal from noise				***Signal***	***Status***	***Auditory***
	Process Signals	*Respond to signals*	***Signal***	***Process***				
		Transduce/convert signal				***Signal***	***Status***	***Auditory***
Process Information		*Chemical (odour, taste, etc.)*				***Signal***	***Status***	***Olfactory***
		Electrical/Magnetic					***Electrical/Electromagnetic***	
		Light-non-visible spectrum				***Energy***	***Electromagnetic***	***Optical***
	Send Signal	*Light-visible spectrum*	***Signal***	***Indicate***	***Display***		***Electromagnetic***	***Optical***
		Sound					***Status***	***Auditory***
		Tactile				***Signal***	***Status***	***Tactile***
		Vibratory					***Status***	***Tactile***

		Atmospheric conditions						
		Balance/gravity/orientation						
		Body awareness						
		Chemical (odour, taste, etc.)						
		Disease						
		Light (non-visible spectrum)						
		Light (visible spectrum)						
	Sense Signal/Environment cues	*Motion*	***Signal***	***Sense***	***Detect/Measure***			
		Pain						
		Shape and pattern						
		Sound						
		Sound and other vibrations						
		Tactile						
		Temperature						
		Time and day length						
	Compute		***Signal***	***Process***				
	Learn							
	Encode/Decode		***Convert***					
		Catalyse chemical reactions					***Chemical***	
		Cleave halogens from organic compounds				***Energy***	***Chemical***	
	Chemically break down	*Cleave heavy metals from organic compounds*	***Branch***	***Separate***	***Divide***		***Chemical***	
		Other inorganic compounds				***Material***	***Solid***	
Break Down		*Other organic compounds*				***Energy***	***Chemical***	
		Polymers				***Material***	***Solid***	
	Physically break down	*Abiotic materials*	***Branch***	***Separate***	***Divide***	***Material***	***Mixture***	***Solid-Solid***
		Biotic materials					***Mixture***	***Solid-Solid***
		Bulk solids				***Material***	***Solid***	
		Chemical entities					***Solid***	
		Energy				***Energy***		
	Capture, absorb, or filter	*Gases*	***Provision/Branch***	***Store/Separate***	***Collect/Extract***	***Material***	***Gas***	
		Liquid				***Material***	***Liquid***	
		Organism				***Material***	***Solid***	
		Solid particles				***Material***	***Mixture***	***Solid-Solid***
Get, Store, or Distribute Resources		*Bulk solids*				***Material***	***Solid***	
		Chemical entities						
	Store	*Energy*	***Provision***	***Store***		***Energy***		
		Gases				***Material***	***Gas***	
		Liquids				***Material***	***Liquid***	
		Solid particles				***Material***	***Mixture***	***Solid-Solid***
		Energy				***Energy***		
	Distribute	*Gases*	***Branch***	***Distribute***		***Material***	***Gas***	
		Liquids				***Material***	***Liquid***	

		Solids
	Expel	*Gases*
		Liquids
		Solid

			Material	***Solid***	
Channel	***Export***		***Material***	***Gas***	
			Material	***Liquid***	
			Material	***Solid***	

Appendix E

E.1 – Test Case A: Venus flytrap integrated model

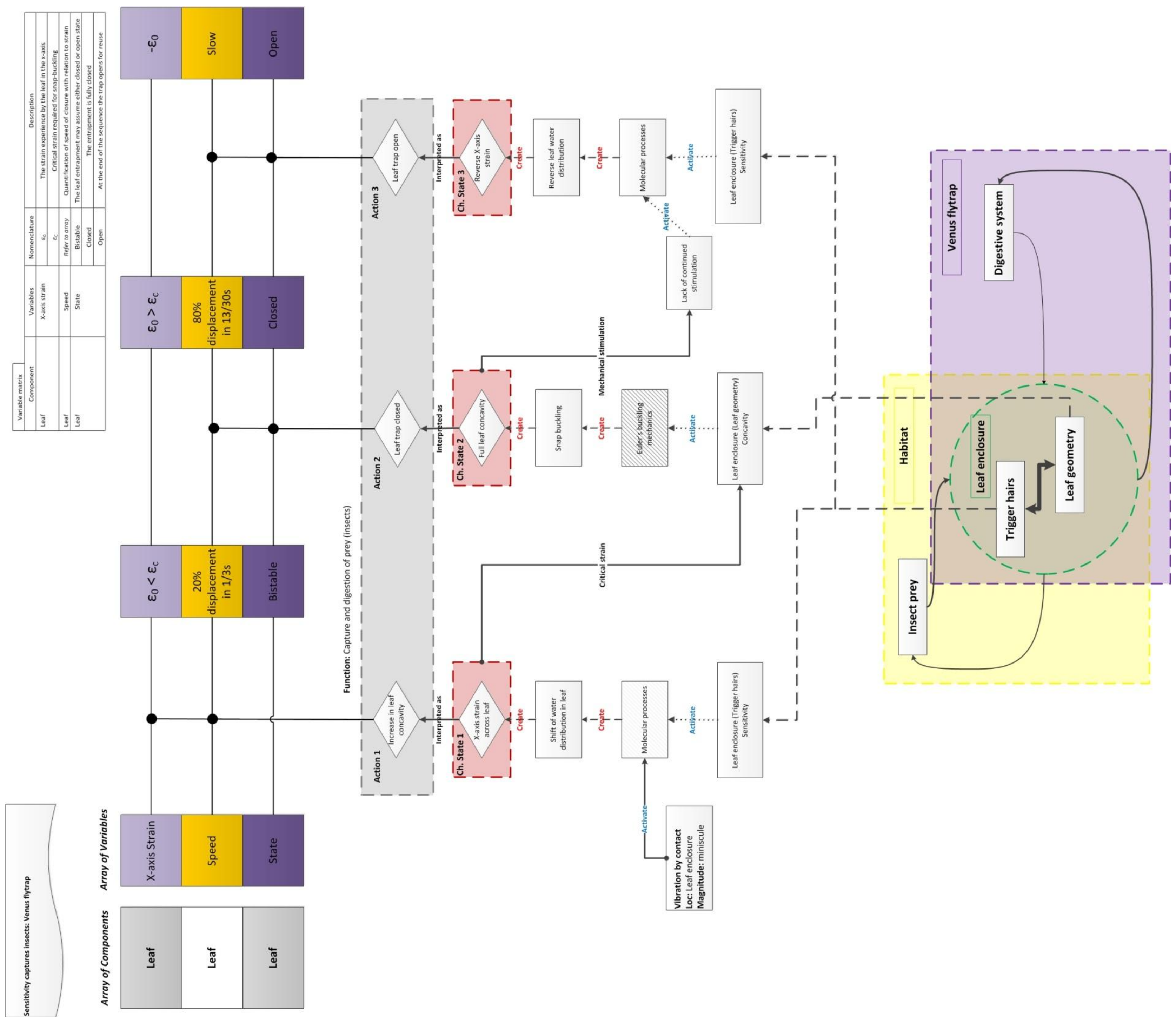


Figure E.1 Venus flytrap integrated model

E.2 – Test Case A: Platypus Bill SAPPhIRE-DANE integrated model

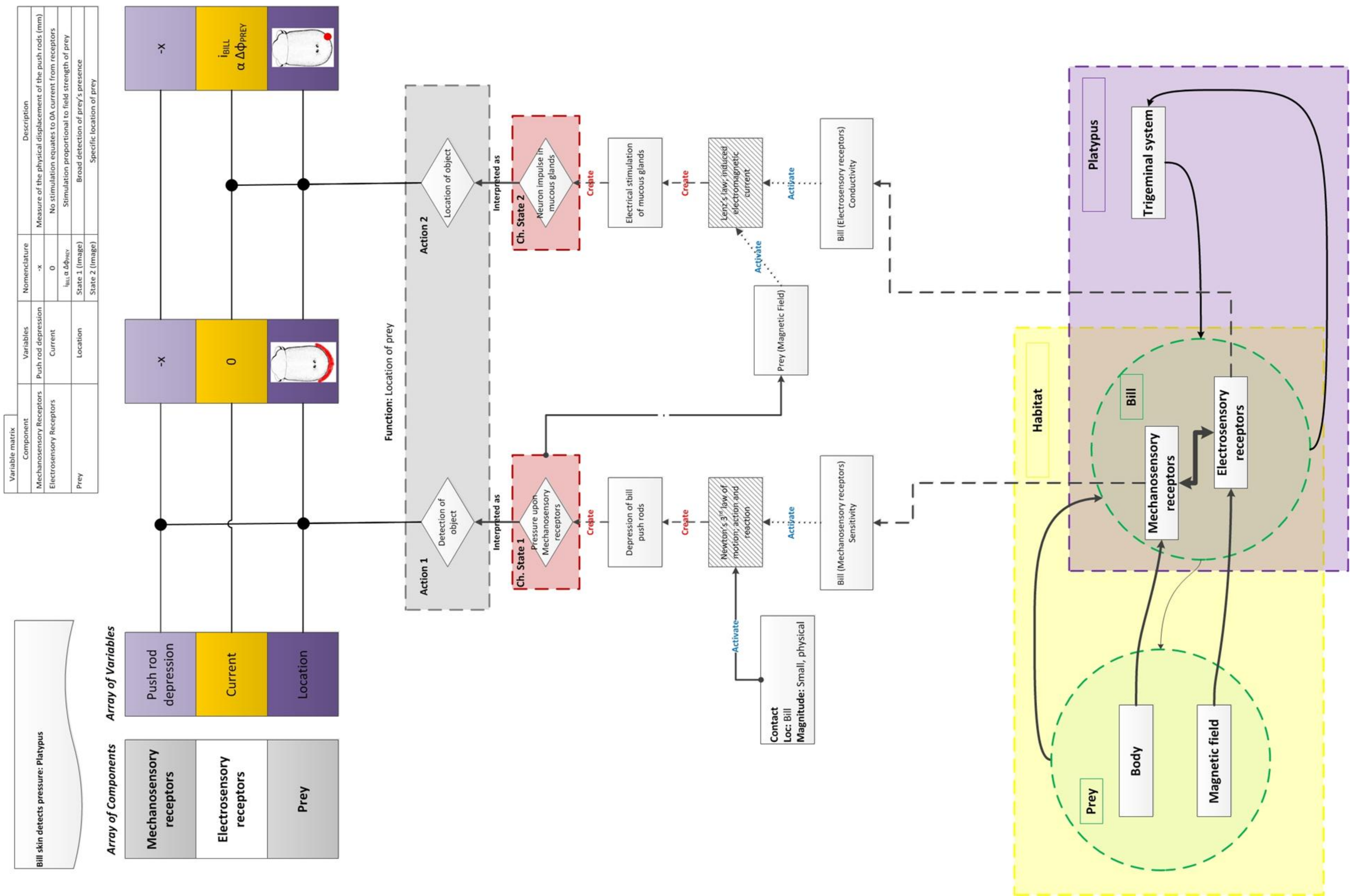


Figure E.2 Platypus Bill SAPPhIRE-DANE integrated model

E.3 – Test Case A: Star-nosed mole SAPPhIRE-DANE integrated model

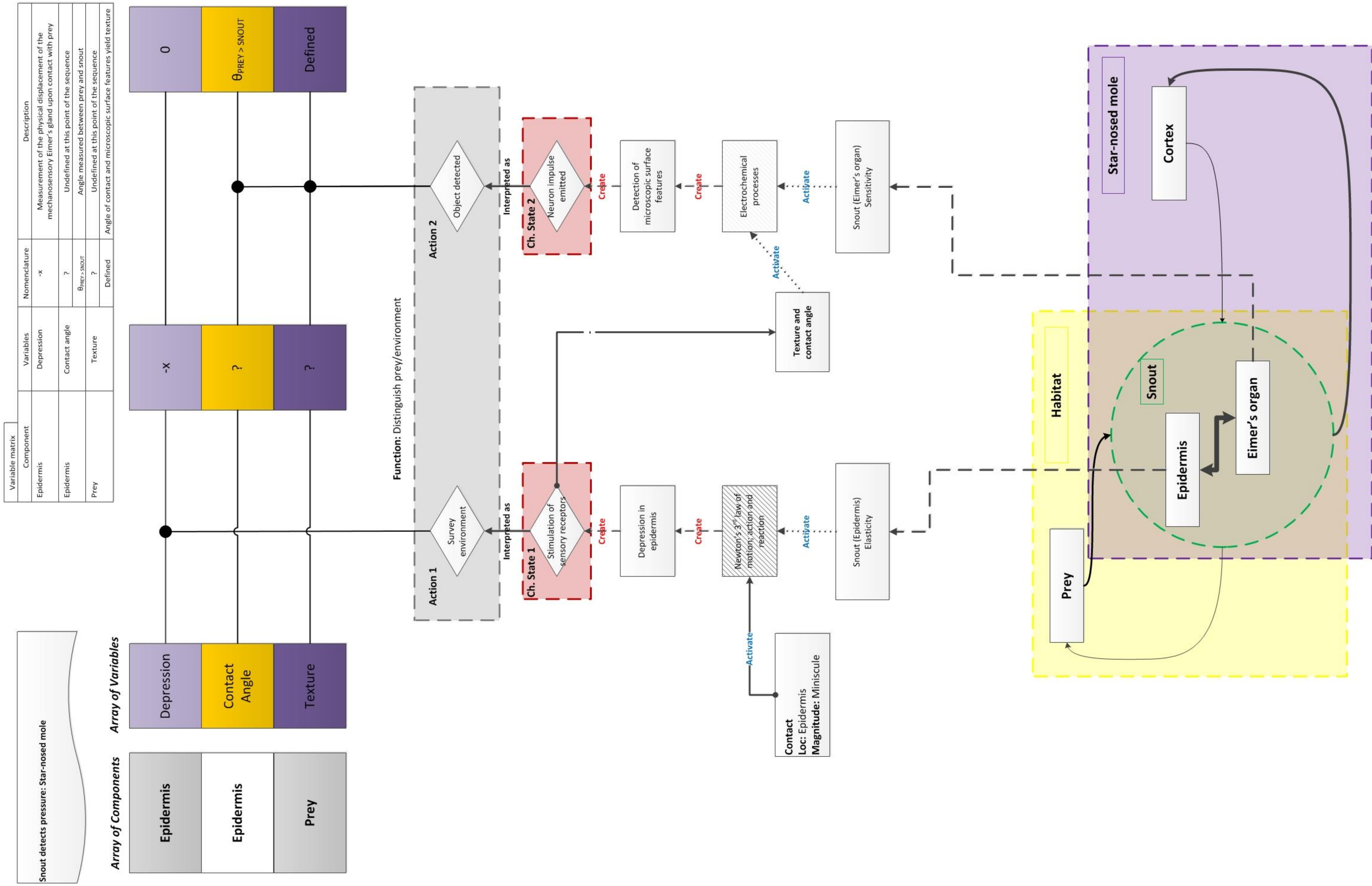


Figure E.3 Star-nosed mole SAPPhIRE-DANE integrated model

E.4 – Test Case B: Blue mussel SAPPhIRE-DANE integrated model

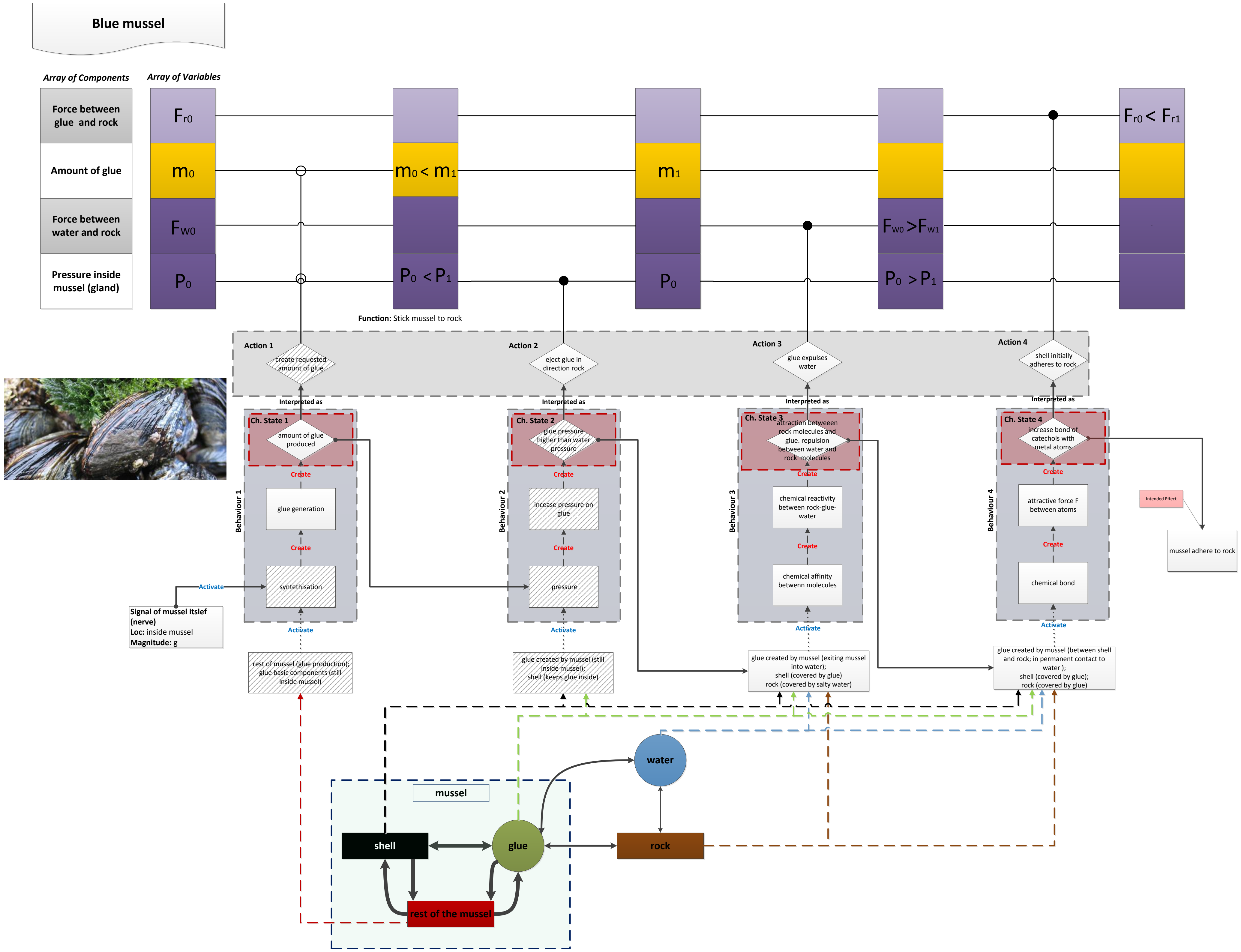


Figure E.4 Blue mussel SAPPhIRE-DANE integrated model

E.5 – Test Case B: Hooked beak SAPPhIRE-DANE integrated model

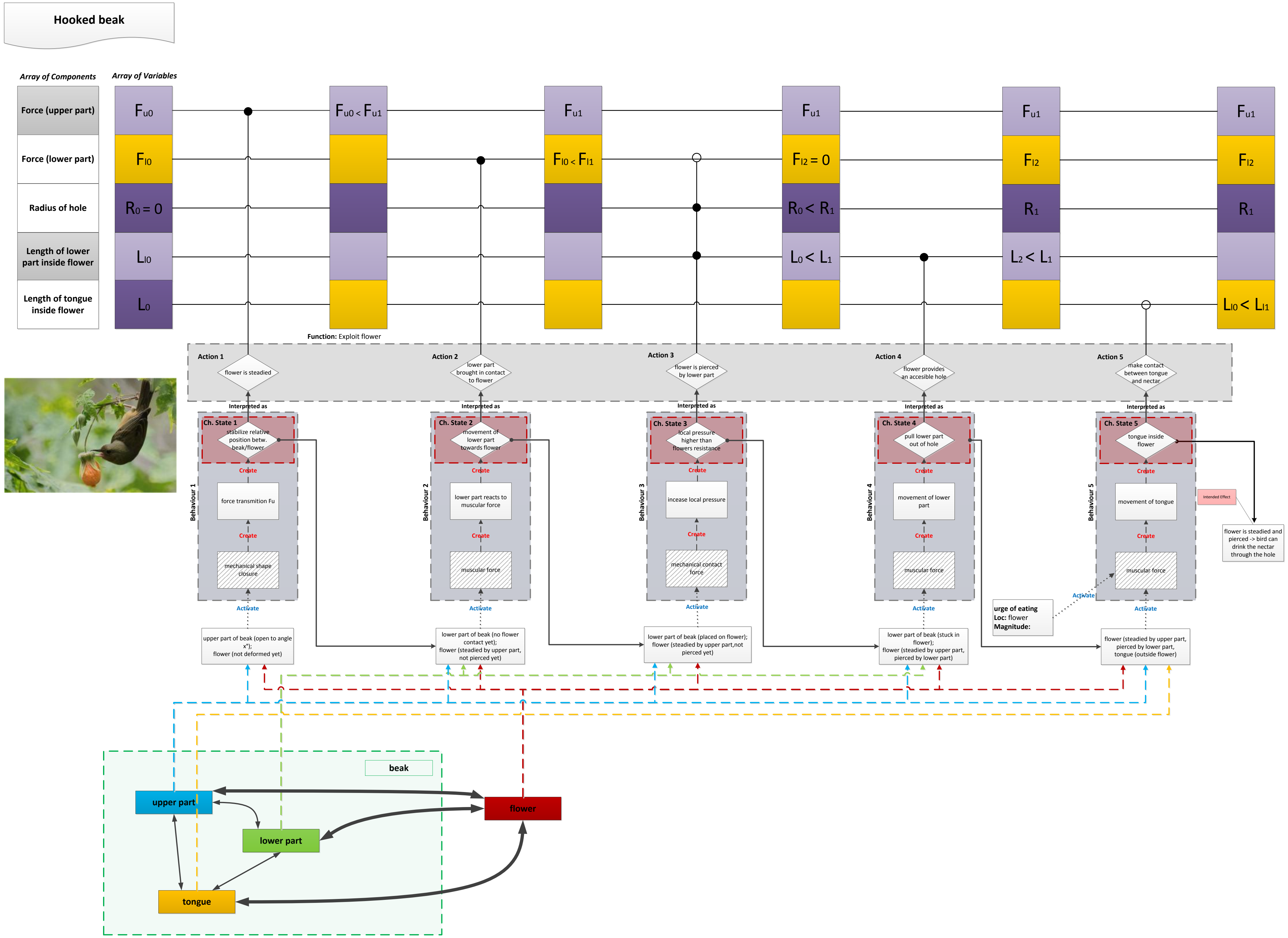


Figure E.5 Hooked beak SAPPhIRE-DANE integrated model

E.6 – Test Case B: Perching bird SAPPhIRE-DANE integrated model

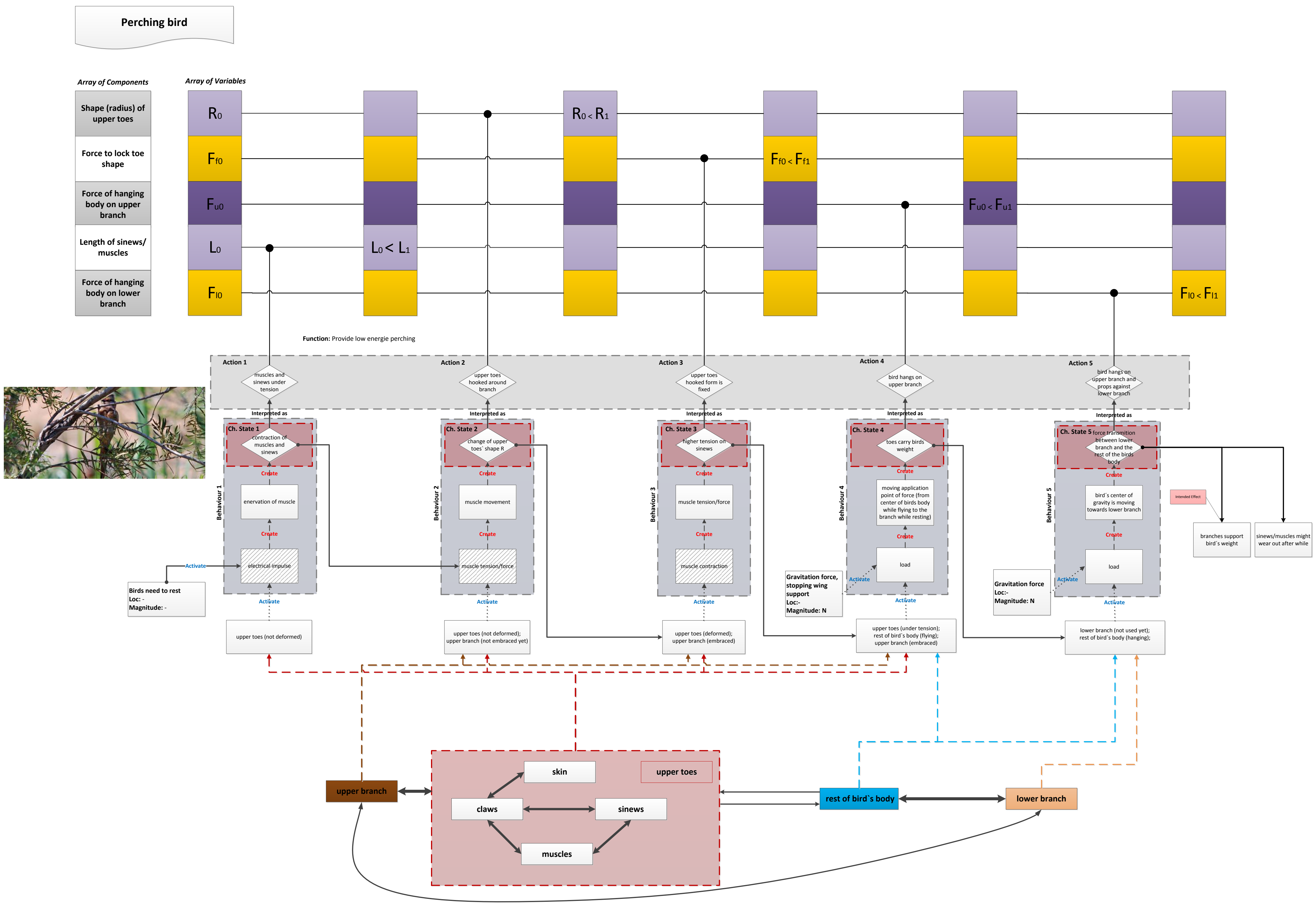


Figure E.6 Perching bird SAPPhIRE-DANE integrated model

E.7 – Test Case B: Ant raft SAPPhIRE-DANE integrated model

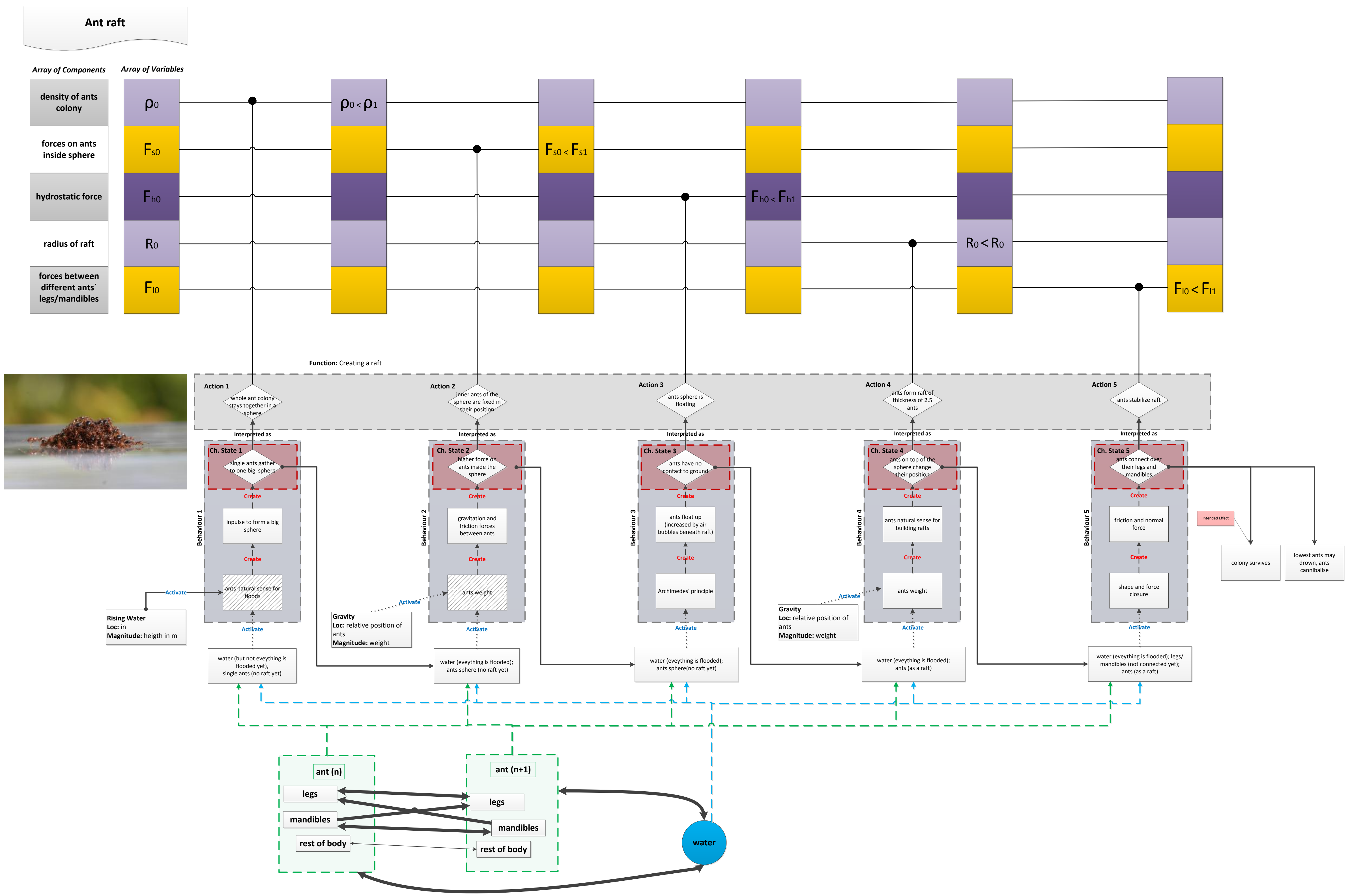


Figure E.7 Ant raft SAPPhIRE-DANE integrated model

E.8 – Test Case B: Ant raft in detail SAPPhIRE-DANE integrated model

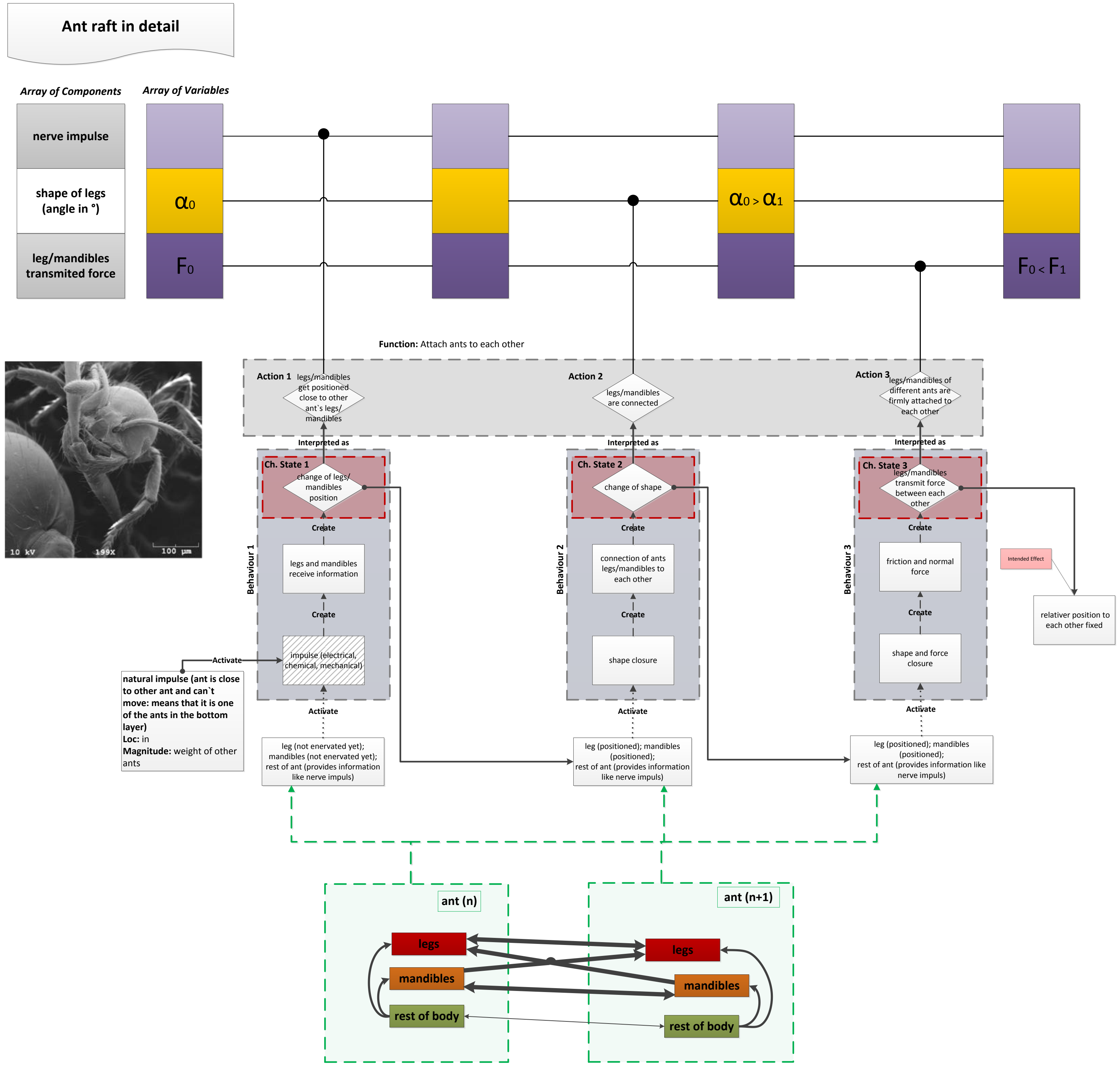


Figure E.8 Ant raft in detail SAPPhIRE-DANE integrated model

E.9 – Test Case C: Tortoise SAPPhIRE-DANE integrated model

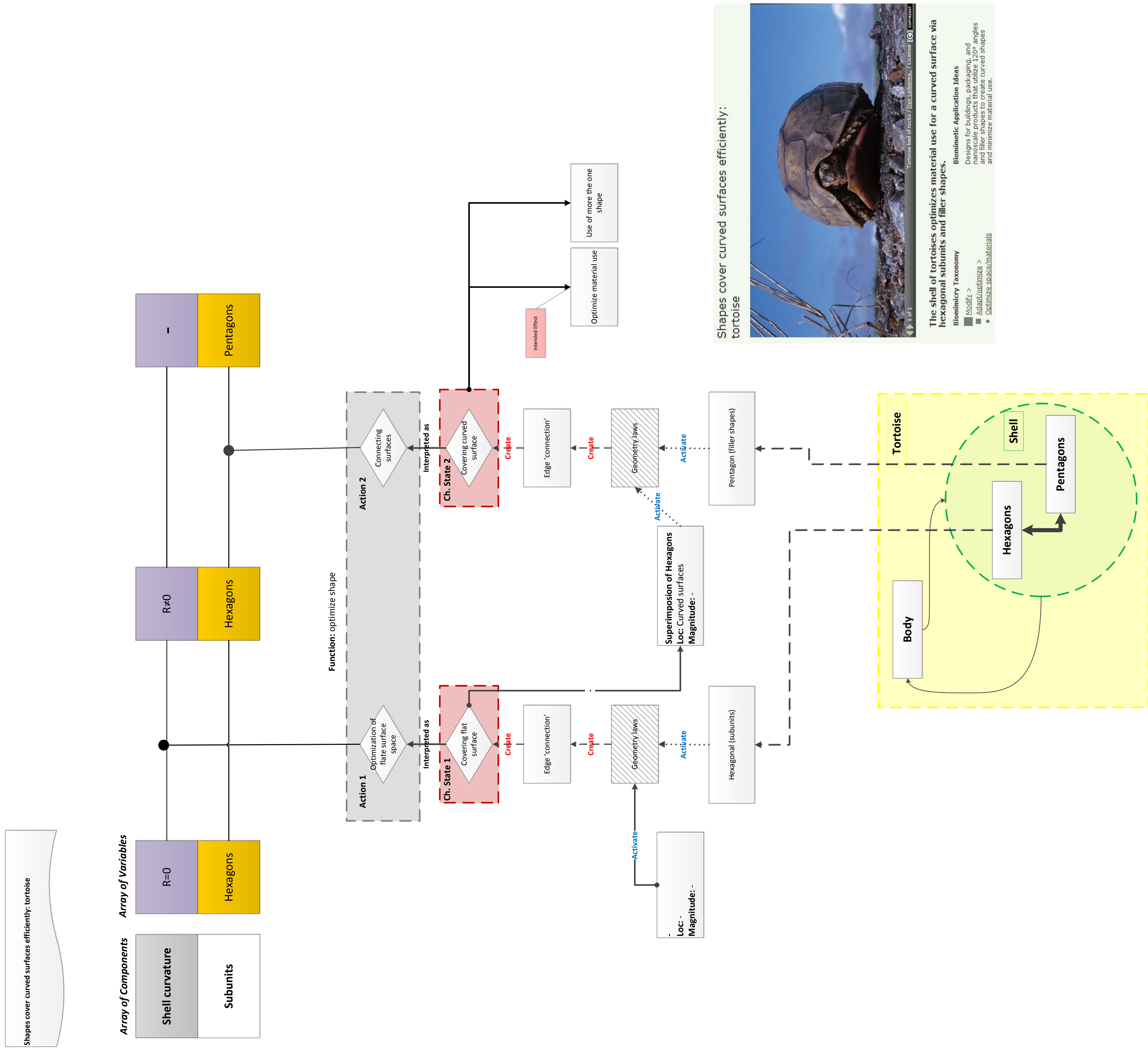


Figure E.9 Tortoise SAPPhIRE-DANE integrated model

E.10 – Test Case C: Red oak roller weevil SAPPhIRE-DANE integrated model

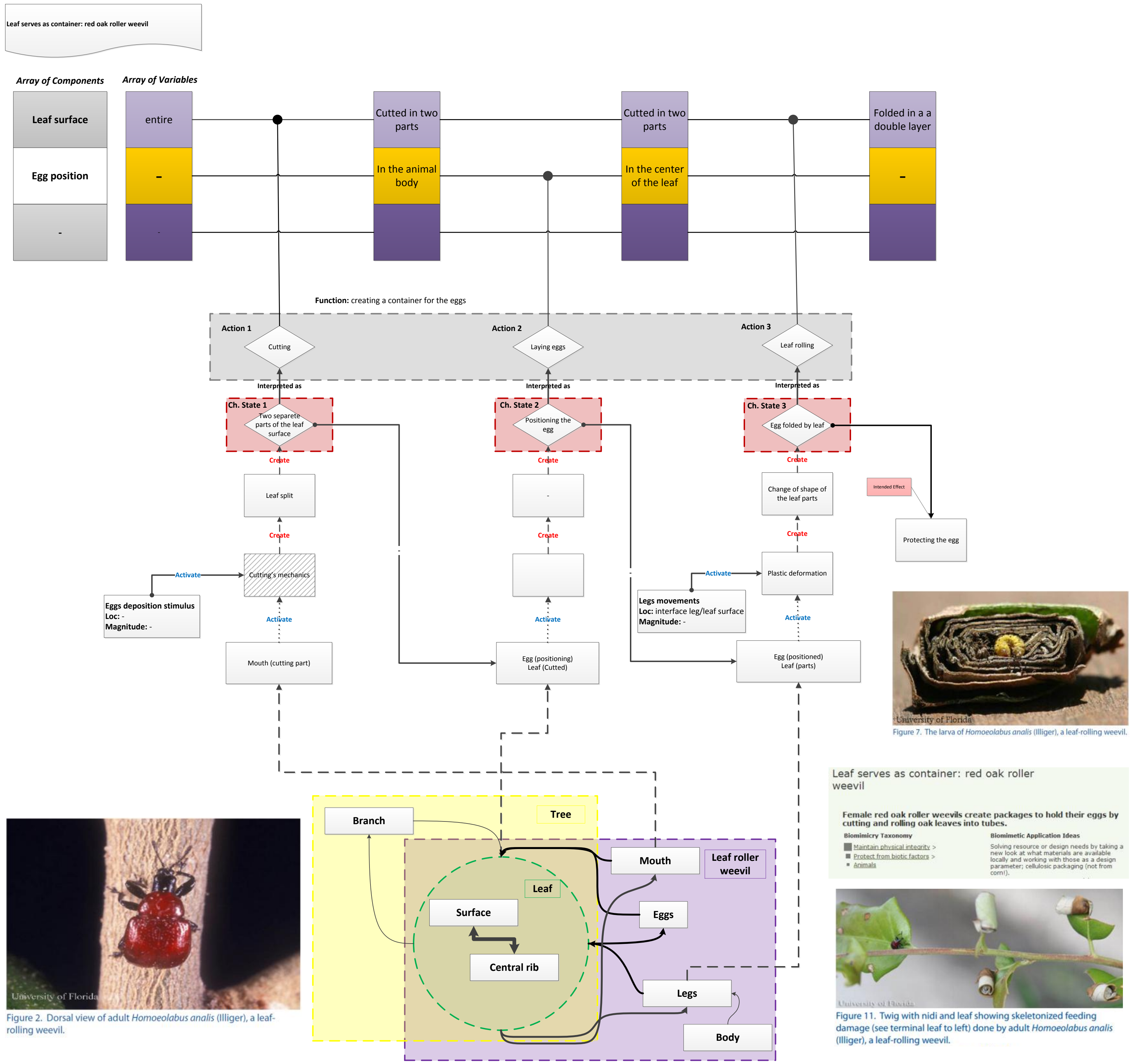


Figure E.10 Red oak roller weevil SAPPhIRE-DANE integrated model

E.11 – Test Case D: Earthworm SAPPhIRE-DANE integrated model

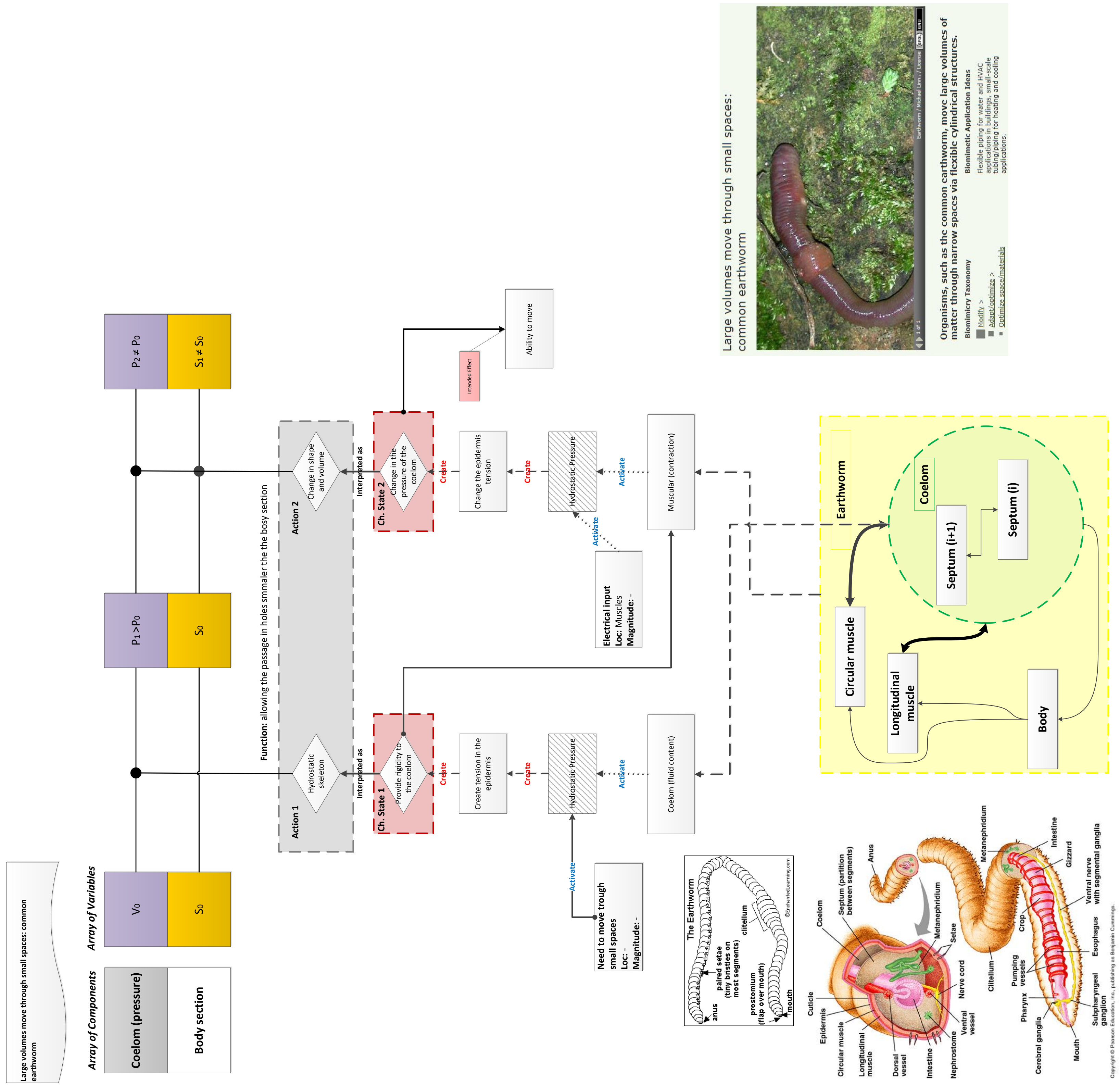


Figure E.11 Earthworm SAPPhIRE-DANE integrated model

E.12 – Test Case D: Thatcheria mirabilis SAPPhIRE-DANE integrated model

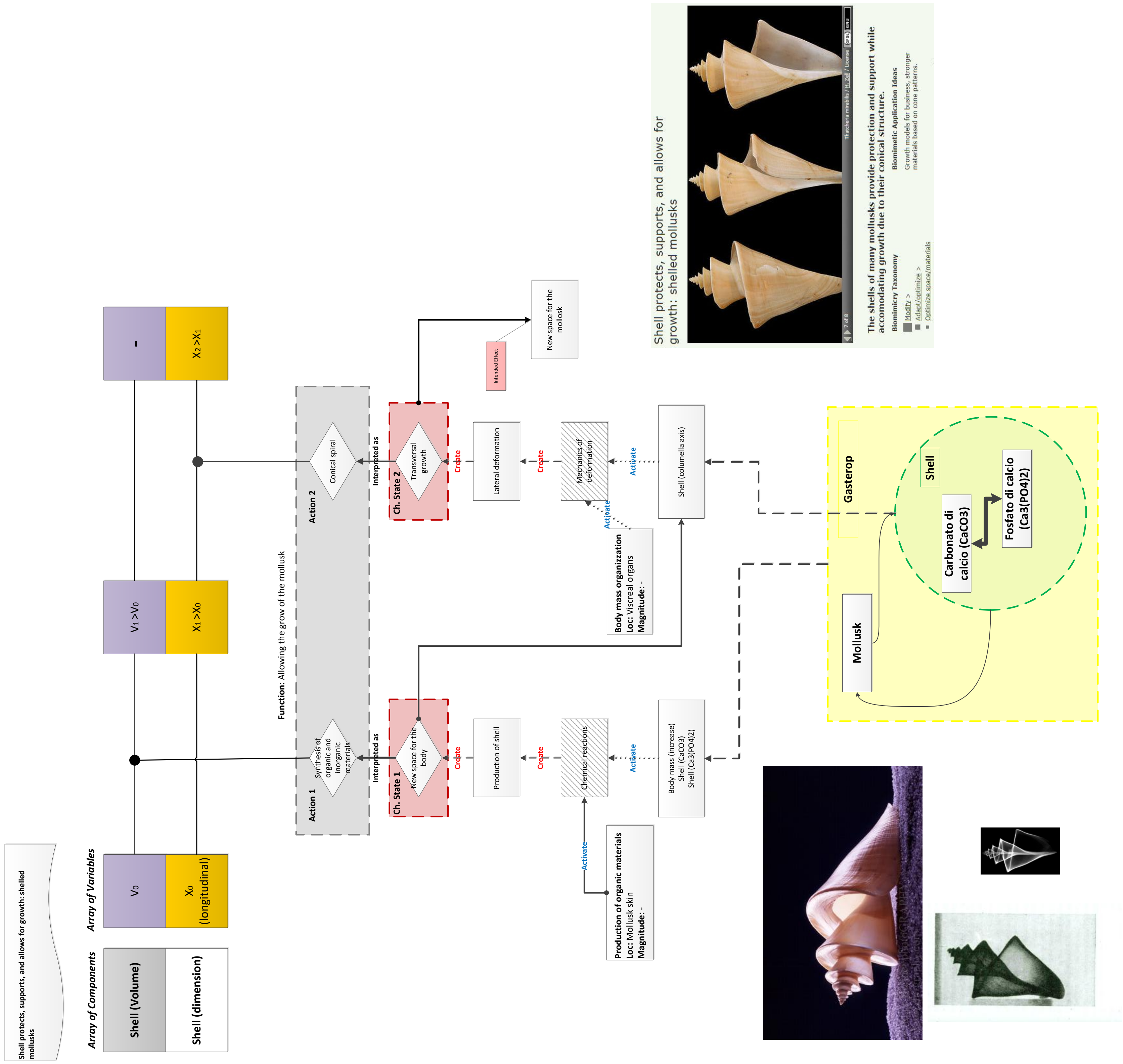


Figure E.12 Thatcheria mirabilis SAPPhIRE-DANE integrated model

E.13 – Test Case D: Arthropod SAPPhIRE-DANE integrated model

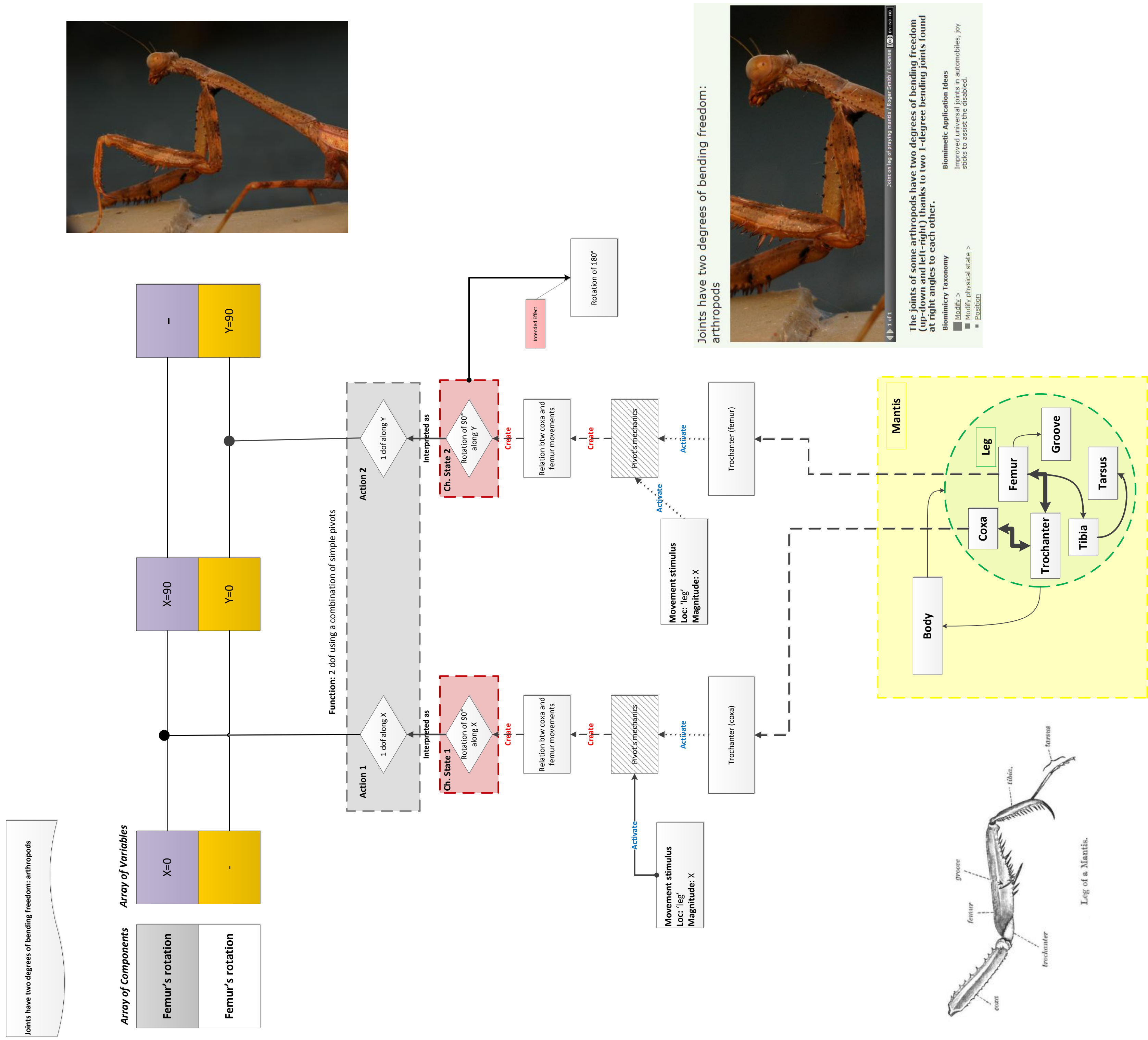


Figure E.13 Arthropod SAPPhIRE-DANE integrated model

Appendix F

F.1 – Methodology Questionnaire: Experiment N° 1

Stage 0 – Task Clarification

Was it possible to achieve the expected result?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- [ ] *Absolutely inappropriate*
- [ ] *Inappropriate*
- [ ] *Slightly inappropriate*
- [ ] *Neutral*
- [ ] *Slightly appropriate*
- [x] *Appropriate*
- [ ] *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- [x] *No*
- [ ] *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- [ ] *No*
- [x] *Partially*

- ☐ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

The physical dimension data was late in being received such that the task was not completed *on schedule*, however other than this every necessity was provided to complete the task.

Do you have any better ideas to carry on the task?

- ☐ *No*
- ☑ *Yes*

If the answer is *Yes,* could you describe it?

Require of the student a brief review of the information contained with *Chapter 5 of Pahl et al. - 2007 - Engineering Design A Systematic Approach* to facilitate easier transition into thesis and to solidify understanding of the requirement list construction and engineering design approach.

Stage 1 – Problem Definition

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☐ *Appropriate*
- ☑ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Stage 2 – Reframe the Problem

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*

- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

The correlation matrix required updating for new articles on database.

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

e.g. CAD, Function Modeling Software, Dictionary, etc.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Stage 3 – "Biological Solution" Search

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate*,* could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☐ *No*
- ☑ *Yes*

If the answer is *Yes,* could you describe it?

Stage 4 – Definition of the “Biological Solution”

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☐ *Appropriate*
- ☑ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Microsoft Visio 2010 (Free trial available, no issue in acquiring)

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☐ *No*
- ☑ *Yes*

If the answer is *Yes,* could you describe it?

Include the summary of articles as a requirement of stage 3 – sources of inspiration, rather than progress from stage 3 and then require the information to be summarized.

Step 5 – Principle Extraction

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☐ *Appropriate*
- ☑ *Absolutely appropriate*

If the tools are inappropriate*,* could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Stage 6 – Design Phase

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☐ *Appropriate*
- ☑ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the stage?

E.g. CAD, Function Modeling Software, Dictionary, etc.

Autodesk Inventor (Free student download); Solidworks

Did you have enough knowledge, in advance or prepared, to carry on the task?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- [ ] *No*
- [x] *Yes*

If the answer is *Yes,* could you describe it?

Literature review of the chapter from Pahl relating to engineering design as a section of the stage.

General questions

Which step was the most difficult?

- [ ] *Step 0 – Task Clarification*
- [ ] *Stage 1 – Problem Definition*
- [ ] *Stage 2 – Reframe the Problem*
- [ ] *Stage 3 – "Biological Solution" Search*
- [x] *Stage 4 – Definition of the "Biological Solution"*
- [ ] *Stage 5 – Principle Extraction*
- [ ] *Stage 6 – Design Phase*

Could you briefly describe why?

Lack of structure did not make it difficult, but required multiple revisions prior to correct model

Which stage was the most intuitive?

- ☐ *Stage 0 – Task Clarification*
- ☐ *Stage 1 – Problem Definition*
- ☐ *Stage 2 – Reframe the Problem*
- ☐ *Stage 3 – "Biological Solution" Search*
- ☐ *Stage 4 – Definition of the "Biological Solution"*
- ☐ *Stage 5 – Principle Extraction*
- ☑ *Stage 6 – Design Phase*

Could you briefly describe why?

After progressing through the previous stages, the development of a solution was organic.

How much effort into time did you put for each stage?

- *Stage 0:*
  - *8 hours*
- *Stage 1:*
  - *12 hours*
- *Stage 2:*
  - *6 hours*
- *Stage 3:*
  - *4 hours*
- *Stage 4:*
  - *20 hours*
- *Stage 5:*
  - *8 hours*
- *Stage 6:*
  - *30 hours*

Could you express your level of Satisfaction for the overall method?

- ☐ *Completely dissatisfied*
- ☐ *Mostly dissatisfied*
- ☐ *Somewhat dissatisfied*
- ☐ *Neither satisfied or dissatisfied*
- ☐ *Somewhat satisfied*
- ☐ *Mostly satisfied*

✓ *Completely satisfied*

Could you briefly describe why?

The existing structure is explicit and logical and all information required is made available to the student; it provides a manner by which a biomimetic design is able to be formulated organically.

F.2 – Methodology Questionnaire: Experiment N° 2

Step 0 – Requirements Identification

Was it possible to achieve the expected result?

- ☐ *No*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate*,* could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

Which kind of "assistance" it has been necessary in order to carry on the step?

Word and EXCEL, Dictionary

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

Step 1 – Problem Definition

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the step?

Power Point, EXCEL

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☑ *Partially*

- ☐ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

I think in the beginning my definition of function and functional design in general was not very good.

Do you have any better ideas to carry on the task?

- ☐ *No*
- ✓ *Yes*

If the answer is *Yes,* could you describe it?

Maybe provide a number of function definitions and more functional modeling methods, which can be used instantly. The book of (PAHL ET AL., 2007) might still be a little bit too theoretically in the approach of functional models.

Step 2 – Reframe the Problem

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ✓ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☐ *Appropriate*
- ✓ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- [x] *No*
- [ ] *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the step?

EXCEL

Did you have enough knowledge, in advance or prepared, to carry on the task?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- [x] *No*
- [ ] *Yes*

Step 3 – Biological Solution Search

Was it possible to achieve the expected result?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- [ ] *Absolutely inappropriate*
- [ ] *Inappropriate*
- [ ] *Slightly inappropriate*
- [ ] *Neutral*
- [ ] *Slightly appropriate*
- [ ] *Appropriate*

- [x] *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- [ ] *No*
- [x] *Yes*

If the answer is *Yes,* could you describe it?

Maybe a description of how to evaluate alternatives would be helpful for the guidelines.

Which kind of "assistance" it has been necessary in order to carry on the step?

EXCEL

Did you have enough knowledge, in advance or prepared, to carry on the task?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- [x] *No*
- [ ] *Yes*

If the answer is *Yes,* could you describe it?

Step 4 – Definition of the Biological Solution

Was it possible to achieve the expected result?

- [ ] *No*
- [ ] *Partially*
- [x] *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the step?

Visio format example for SAPPhIRE-DANE model

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☑ *Partially*
- ☐ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

The general approach of the step 4 was quite clear. Nevertheless, the definitions of the different terms were sometimes slightly confusing. Thus, I think it took some time until I really understood the SAPPhIRE-DANE model. Maybe it could be made easier to understand by giving even more examples.

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

Step 5 – Principle Extraction

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate*,* could you briefly describe why?

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the step?

The morphological matrix was really helpful to structure and combine solutions. Visio was used for sketches.

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☐ *No*
- ☑ *Yes*

If the answer is *Yes,* could you describe it?

Maybe it would be good to add the morphological matrix explicitly to the guidelines, as it really was a core tool of this step.

Step 6 – Principle Application

Was it possible to achieve the expected result?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you describe why it was not possible?

Are the proposed tools appropriate to achieve the expected result?

- ☐ *Absolutely inappropriate*
- ☐ *Inappropriate*
- ☐ *Slightly inappropriate*
- ☐ *Neutral*
- ☐ *Slightly appropriate*
- ☑ *Appropriate*
- ☐ *Absolutely appropriate*

If the tools are inappropriate, could you briefly describe why?

Though the approach was appropriate it would be nice to have a given definition, which provides a more exact progress of describing conceptual solutions.

Do the tools have some inability or specific lack according to your experience?

- ☑ *No*
- ☐ *Yes*

If the answer is *Yes,* could you describe it?

Which kind of "assistance" it has been necessary in order to carry on the step?

CAD

Did you have enough knowledge, in advance or prepared, to carry on the task?

- ☐ *No*
- ☐ *Partially*
- ☑ *Yes*

If the answer is *Partially* or *No,* could you list which knowledge it was necessary to carry on the task?

Do you have any better ideas to carry on the task?

- ☑ *No*
- ☐ *Yes*

General questions

Which step was the most difficult?

- ☐ *Step 0 – Task Clarification*
- ☐ *Step 1 – Problem Definition*
- ☐ *Step 2 – Reframe the Problem*
- ☐ *Step 3 – Biological Solution Search*
- ☑ *Step 4 – Definition of the "Biological Solution"*
- ☐ *Step 5 – Principle Extraction*
- ☐ *Step 6 – Principle Application*

Could you briefly describe why?

In the beginning, it was not too easy to understand SAPPhIRE-DANE and its terms.

Which step was the most intuitive?

- ☐ *Step 0 – Task Clarification*
- ☐ *Step 1 – Problem Definition*
- ☐ *Step 2 – Reframe the Problem*
- ☐ *Step 3 – Biological Solution Search*
- ☐ *Step 4 – Definition of the "Biological Solution"*
- ☐ *Step 5 – Principle Extraction*

☑ *Step 6 – Principle Application*

Could you briefly describe why?

Because most engineers are probably able to describe product by sketches or words in some way.

How much effort into time did you put for each step?

- *Step 0:*
  - *2 days*
- *Step 1:*
  - *2 days*
- *Step 2:*
  - *1 day*
- *Step 3:*
  - *5 days*
- *Step 4:*
  - *5 days*
- *Step 5:*
  - *9 days*
- *Step 6:*
  - *4 days*

Could you express your level of satisfaction for the overall method?

☐ *Completely dissatisfied*

☐ *Mostly dissatisfied*

☐ *Somewhat dissatisfied*

☐ *Neither satisfied or dissatisfied*

☐ *Somewhat satisfied*

☑ *Mostly satisfied*

☐ *Completely satisfied*

Could you briefly describe why?

It was a very logic approach with one-step basing on the other, which was really good. In some situations, it might have been helpful to have more specific guidelines than the ones from (PAHL ET AL., 2007) in order not to search in it and to be faster.

Appendix G

The meaning of Function in Biology

*The aim of this survey is to deepen the **understanding** of the **concept of Function in Biology** and to recognize the perceived meaning by biologists of the terms typically used in Engineering Design to build functional models*

*The ultimate goal of this study is to **improve** the **communication between biologists** and **designers***

There are 19 questions in this survey

Contacts

This is an optional question

If you are interested in receiving a report on the outcomes of this survey, please leave your contacts details here below

1. Name

Please write your answer(s) here:

- Name
- Surname
- e-mail address

Introductory questions

In order to be able to give the correct evaluation to your answers it is fundamental know the following details about you and your job

2. Introductory questions *

Please write your answer(s) here:

- Gender
- Age
- Education
- Profession

For statistical reasons we need some general information about the participants to the survey; these data will be used solely for analyzing the distribution of answers to the following questions.

3. Have you ever heard anything about Bio-Inspired Design? Are you familiar with it? *

Please choose **only one** of the following:

- Not at all familiar
- Slightly familiar
- Somewhat familiar
- Moderately familiar
- Extremely familiar

Bio-Inspired Design (BID): *is an approach to design that espouses the adaptation of a function and mechanism in biological sciences to solve engineering design problems* (Helms et al., 2009)

Fundamental information for a biological description

Fundamental information for a biological description of a living organism

4. What is the most typical object of study in your field of interest? *

Please choose **all** that apply:

- ecosystem
- system
- physiology
- morphology
- micromorphology
- composition
- molecular mechanism
- Other:

5. With respect to the answer to the previous question, as a biologist which feature(s) is(are) more interesting to describe?

Please rank your features by importance according to your experience - see examples below.

Please write your answer(s) here:

- Feature N°1 (very important)
- Feature N°2
- Feature N°3

- Feature N°4
- Feature N°5 (less important)

Examples:

Object of study *(list of features)*

- ***ecosystem*** *(level of interaction, use of resources, etc.)*
- ***system*** *(relationships among components, number of elements, etc.)*
- ***physiology*** *(chemical function, physical function, etc.)*
- ***morphology*** *(shape, structure, etc.)*
- ***micromorphology*** *(patterns, composition, etc.)*
- ***composition*** *(constituents, chemical properties, etc.)*
- ***molecular mechanism*** *(interaction between proteins, ways of interaction regulation, etc.)*

6. How important is an exhaustive description of the environment to make a useful representation of a natural system/phenomenon in your field? *

Please choose **only one** of the following:

- Not at all important
- Low important
- Slightly important
- Neutral
- Moderately important
- Very important
- Extremely important

An exemplary representation of the natural system [e.g. protein, cell, organ, etc.] and its environment is given in the figure below

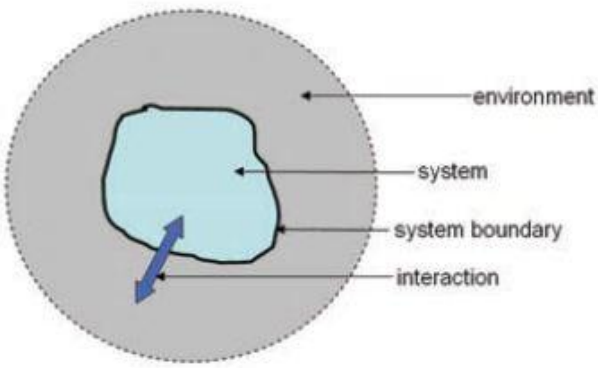
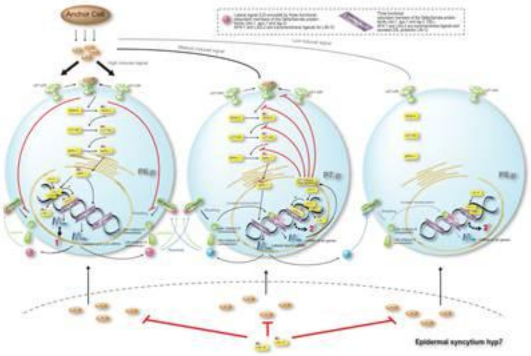


Figure G.1 System and Environment Interaction (Chakrabarti & Srinivasan, 2009)

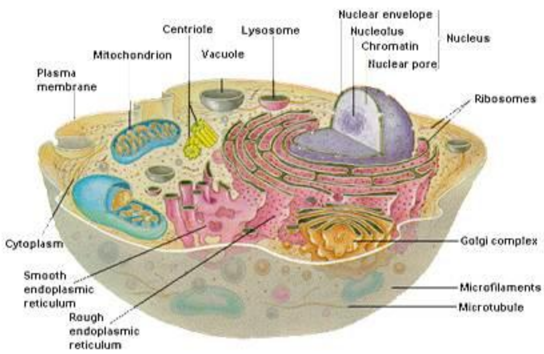
7. Which is the way to describe the interactions between the natural system and the environment in your field? *

Please number each box in order of preference from 1 to 5

- ☐ Textual descriptions
- ☐ Graphs, Charts, Data tables
- ☐ Diagrams
- ☐ Drawings
- ☐ Pictures



e.g. DIAGRAM



e.g. DRAWING

e.g. PICTURE

Figure G.2 Diagram, Drawing and Picture of a Natural System

8. What definition would you give to the expression: “Biological Function”? *

Please write your answer here:

- ☐ ______________________________

Name-Label of the items

Questions about the definitions of the items of the functional-causal models used in engineering design

9. Which Name-Label would you give to the following definitions related to a biological system/subsystem/feature?

Please choose the appropriate response for each item:

	Action	Behaviour	Effect	Feature	Flow	Function	Goal	Input	Model	None	Object	Organ	Output	Part	Physical Law	Physical Phenomenon	Property	Quality	State	Structure
a physical variable that crosses the system boundary, and is essential for an interaction between the system and its environment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
a principle of nature that underlies and governs an interaction	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
a property of the system (or its environment) that is involved in an interaction	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
a set of physical components and interfaces that constitute the system of interest and its environment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
a set of properties and conditions of the system and its environment required for an interaction between them	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
an abstract description or high-level interpretation of an interaction between the system and its environment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
an interaction between the system and its environment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
the elemets of the natural system, the material arragment of these elements and their connectivity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
the natural system's action or processes in given circustances of the natural environment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
the results of the natural system's behiours	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Definitions of the items

Questions about the definitions of the items of the functional-causal models used in engineering

Is the definition, provided by the Oxford English Dictionary (www.oed.com)**, adequate in your field?**

10. Action: ***Something done or performed, a deed, an act; (in pl.) habitual or ordinary deeds, conduct.***

Please choose **only one** of the following:

- ☐ Inappropriate
- ☐ Slightly inappropriate
- ☐ Slightly appropriate
- ☐ Appropriate

Make a comment on your choice here:

- ☐ ___________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

11. Behavior: ***The manner in which a thing acts under specified conditions or circumstances, or in relation to other things***

Please choose **only one** of the following:

- ☐ Inappropriate
- ☐ Slightly inappropriate
- ☐ Slightly appropriate
- ☐ Appropriate

Make a comment on your choice here:

- ☐ ___________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

12. Effect: ***The physical result of the action of a force***

Please choose **only one** of the following:

- Inappropriate
- Slightly inappropriate
- Slightly appropriate
- Appropriate

Make a comment on your choice here:

- ______________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

13. Function: *The action of performing; discharge or performance of (something)*

Please choose **only one** of the following:

- Inappropriate
- Slightly inappropriate
- Slightly appropriate
- Appropriate

Make a comment on your choice here:

- ______________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

14. Input: *That which is put in or taken in, or which is operated on or utilized by any process or system*

Please choose **only one** of the following:

- Inappropriate
- Slightly inappropriate
- Slightly appropriate
- Appropriate

Make a comment on your choice here:

- ______________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

15. Organ: ***Any of various mechanical devices or A part of an animal or plant body that serves a particular physiological function***

Please choose **only one** of the following:

- Inappropriate
- Slightly inappropriate
- Slightly appropriate
- Appropriate

Make a comment on your choice here:

- ____________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

16. Part: ***A piece or section of something, which together with another or others makes up the whole***

Please choose **only one** of the following:

- Inappropriate
- Slightly inappropriate
- Slightly appropriate
- Appropriate

Make a comment on your choice here:

- ____________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

17. Physical Phenomenon: ***Of or relating to natural phenomena perceived through the senses (as opposed to the mind); of or relating to matter or the material world; natural; tangible, concrete - A thing which appears, or which is perceived or observed.***

Please choose **only one** of the following:

- Inappropriate

- ☐ Slightly inappropriate
- ☐ Slightly appropriate
- ☐ Appropriate

Make a comment on your choice here:

- ☐ ___________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

18. State: ***The combination of circumstances or attributes belonging at a particular time to a person or thing; a particular manner or way of existing as defined by the presence of certain circumstances or attributes; a condition***

Please choose **only one** of the following:

- ☐ Inappropriate
- ☐ Slightly inappropriate
- ☐ Slightly appropriate
- ☐ Appropriate

Make a comment on your choice here:

- ☐ ___________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

19. Structure: The mutual relation of the constituent parts or elements of a whole as determining its peculiar nature or character; make, frame

Please choose **only one** of the following:

- ☐ Inappropriate
- ☐ Slightly inappropriate
- ☐ Slightly appropriate
- ☐ Appropriate

Make a comment on your choice here:

- ☐ ___________________________

In the case of **inappropriateness**, **which definition would you give to this Name-Label?**

Please insert, into the comment box, your preferred definition according to your experience

List of Abbreviations (Foldable)

AI	Artificial Intelligence
B	Behaviour
BID	Bio-Inspired Design
BIP	Bio-Inspired Product
BT	Biomimicry Taxonomy
CD	Conceptual Design
CPD	Causal Process Description
CS	Case Study
DANE	Design by Analogy to Nature Engine
F	Function
FB	Functional Basis
FBS	Function-Behaviour-Structure
FR	Functional Representation
NIST	National Institute of Standard and Technologies
NIST-FB	NIST-Functional Basis
NSoI	Natural Source of Inspiration
OED	Oxford English Dictionary
PB	Problem
PDD	Product Design and Development
PDP	Product Development Process
PS	Pumping System
RL	Requirements List
RQ	Research Question
S	Structure
SAPPhIRE	(change of) State-Action-Part-Physical Phenomenon-Input-oRgan-Physical Effect
SME	Small-Medium Enterprise
SoA	State of the Art
TC	Test Case