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A Bi-Directional Method for Bionic Design with Examples

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1. Introduction

Design methodologies are essential tools in the design process which provide pathways, goals and technical guidelines for the development of products. These are also critical to minimize the risks and the time of the development process of a product (Kindlein et al., 2003). It should, however, be noted that the use of a method of design for the development of the product does not in itself create or guarantee the success of a product, as this will be subject to a myriad of factors including the level of technical expertise and creativity of who makes use of the method. Previous work by Versos and Coelho (2011-a, 2011-b, 2010) and by Coelho and Versos (2011, 2010) analyzed and compared several methods for guiding bionic design that were available in literature. These analyses, in addition to providing the basis of study for the development of the methodology that is aimed in this chapter, can support designers in the selection process of the bionic design method most appropriate to the problem at hand. Previous work emphasized the necessity of integrating validation activities in bionic design processes. The development and testing of improved methods that provide greater support to designers in the pursuit of activities leading to bionic solutions is the overarching aim that this chapter seeks to contribute to satisfy.

It is up to the designer to have control and decide upon the best option and way forward (Kindlein et al., 2003) in the design process. Thus, it is necessary to specify objectives, requirements and restrictions for the design process, as well as to present and define all possible paths in order to reduce the barriers for progression and to deal with the complexity inherent to the big number of variables involved in the course of the deployment of the method. Guiding the user towards requirements satisfaction and appropriate resolution of the problem at hand is the goal of any design method, including design methods with a bionic character.

As in Nature—an environment in constant adaptation and renewal, where species evolve systematically and only the strongest survive and become adapted to the environment—the planning and development of a product must also ensure an iterative nature of the process and constant reassessment of the design process. The means available to man and his own needs and ambitions are targets of constant change. Therefore, methods for developing a product should allow for continuous adjustment and restructuring.

2. Bi-directional bionic design method proposed

To define the contours of the method of bionic design process developed and that is reported in this book chapter, two possible starting guidelines were considered: guidance in the direction from the bionic solution to the design problem and guidance in the direction from the design problem to the bionic solution. Thus, two method branches (A and B) were developed respecting each of the two alternative orientations considered for the bionic design process. The common steps in both directions of analysis (C1, C2 and C3) consist in the same activities, contain the same description and as such are applicable for the two orientations. The resulting proposition can be observed in summarized form in Tables 1 and 2, a design process starting from the design problem and oriented towards the solution (A) and a design process with orientation from the bionic solution to the design problem (B), respectively.

Steps	Description
A1 - Design brief and problem definition	- Specification of the problem to be solved by identifying the functions that it must carry out, the desired requirements and restrictions involved. - Preparation of the list with the schematic aspects of specification and key environmental and ecological aspects to be observed.
A2 - Reformulation of the problem	- Revision and redefinition of general problems and tasks defined in biological terms and widely applicable. - Questioning how Nature solves the problems or functions that are intended to be solved in the design process.
A3 - Selection of solutions	- Search for biological models and solutions that meet and solve the challenges presented through literature searches, field observations, or using open discussions with biologists and experts.
A4 - Solution analysis	- Identification and morphological analysis of structures, components, processes and functions of the biological solution, related to the problem at hand. - Relating the functions and requirements of the problem with the functions and features of the biological solution.
C1 - Generating concepts	- Development of ideas and concepts (in the form of sketches and 3D models) based on natural models and following the guidelines and principles obtained in the steps of analysis and definition of the biological solution and the problem.
C2 - Validation	- Verification of compliance with the requirements of the problem and validating the gains introduced by the bionic concepts developed through the validation process of the corresponding relationship between the requirements and objectives of the project to achieve the goals established. - Selecting the most appropriate concepts for the next step.
C3 - Detail and finish	- Making technical drawings for manufacturing, detailed descriptions of components, materials, manufacturing processes and all the considerations adequate to the type and purpose of the project. - Construction of prototype and presentation of results.

Table 1. Condensed description of the steps of the method of bionic design developed following the direction from the problem to the solution (A).

Steps	Description
B1 - Solution identification	- Observation of natural phenomena and identification of potential solutions or biological properties with outstanding characteristics, eligible for transfer for application to human problems.
B2 - Analysis of the solution	- Analysis and layout of a number of factors that allow perceiving the shape, structure, organization and principles of the solution. - Extraction of the fundamental principles that motivate the solution.
B3 - Reformulation of the solution	- Deduction of general principles, obtained in the previous step, in particular and in greater details and considering possible links between the biological behaviour of the solution and mechanical behaviour.
B4 - Search for a problem	- Finding, taking into account the data from the previous step, real problems, existing solutions to optimize or emerging needs that can be met with the bionic considerations identified.
B5 - Design brief and association principles	- Identification and outline of the general and specific principles for the operation of the product, the requirements and constraints of the problem and the ecological and environmental aspects to be considered for subsequent association with properties extracted from the analysis of the bionic solution.
C1 - Generating concepts	- Development of ideas and concepts (in the form of sketches and 3D models) based on natural models and following the guidelines and principles obtained in steps of analysis and definition of the biological solution and the problem.
C2 - Validation	- Verification of compliance with the requirements of the problem and validating the gains introduced by the bionic concepts developed through the validation process of the corresponding relationship between the requirements and objectives of the project to achieve the goals established. - Selecting the most appropriate concepts for the next step.
C3 - Detail and finish	- Making technical drawings for construction, detailed descriptions of components, materials, manufacturing processes and all the considerations necessary for the type and purpose of the project. - Construction of prototype and presentation of results.

Table 2. Summarized description of the stages of the bionic design method developed following the orientation from the bionic solution to the design problem (B).

Tables 1 and 2 depict the sequential organization of the methodology, although iterations are possible between the various stages of each of the two directions of analysis considered. This iteration aims to enable refinement and optimization of the design with the right steps and facilitate the analogies between the natural functions of the solution and the desired functions of the problem. In the validation phase it is possible in the methodological process to go back to any previous step. Here the aim is to be able to change, correct or improve certain aspects, taking into account the needs identified through the results of the evaluation performed in previous steps.

In the following sections the activities that are necessary for implementing the steps of both branches of the methodology developed are described.

2.1. Description of the methodology developed for the direction from the design problem to the bionic solution (A)

If the guidance for the project in question follows the direction from the identification of a design problem (a new problem or an existing one), the first task will be to draft a design brief and then defining the problem and carrying out a development process following the steps described in the following sections.

2.1.1. Step A1 – Design brief and problem definition

At this stage the problem or the human need must be specified by conducting a briefing, which should identify the function (or functions) that the project will perform as well as the actual problem and the reasons for its existence. It is also important at this stage to define the target market, i.e. who is involved with the problem and the solution, as well as the definition of where the problem is and, or, where the solution is to be applied.

For the definition of the function or functions that are intended to be carried out by the design, an auxiliary method indicated by Helms et al. (2009) is the functional decomposition of the problem or need, starting with the more complex and general function, which is subsequently decomposed into sub-functions. According to the authors, for each of these sub-functions optimization criteria can thus be defined, which are useful in further evaluation of new solutions, by measuring performance and satisfaction with the optimization criteria.

The existence of a list of requirements and restrictions, subjecting the product, is equally important in this step. Environmental and ecological variables must be included in the list and considered in routine development, production, use and final disposal of the product (Kindlein et al., 2003). Thus, these should be included in the requirements of the problem, aiming to reducing the environmental impact caused by the extraction and processing of the raw material to be used, as well as by the product production, use and the end of useful life, where issues of recycling and biodegradation must be met.

Having a clear definition of the problem, it is necessary to comprehend it in terms of Nature, i.e., translating the roles and functions of the project into sub-functions performed by natural phenomena. This step is defined as the reformulation of the problem.

2.1.2. Step A2 – Reformulation of the problem

According to Helms et al. (2009), in order to find solutions analogous to biology, designers must redefine and reshape the problems and functions in general and widely applicable biological terms, questioning, for example, "how does Nature and biological solutions do (or not do) this? ". As an example, for a function defined in the first stage as "to not suffer falls," recasting this in biological terms could mean "which features in Nature and biological solutions enable resisting, preventing and reducing lack of stability?”

The third step of the method, considering the direction of analyzing the problem towards the solution concerns the search and selection of relevant biological solutions for the design problem.

2.1.3. Step A3 – Selection of solutions

Selecting the solution models that address the nature, and, or the challenges posed, can be done through literature search or fieldwork, involving some knowledge about the habitat of samples to collect (Junior et al., 2002). It can also be done using open discussions with biologists and specialists in this field.

Some of the existing techniques, identified by Helms et al. (2009), to be taken into account in the search are the modification of the restrictions of the problem, often defined strictly and accurately, therefore reducing the search area, thereby enabling a successful search. Thus, for a problem defined as "not to suffer falls," change the restrictions into a larger search space: "stability and resistance to impact." According to those authors, in order to avoid complexity of the systems and their inherent organic nature, often demands solutions that are accessible and simple but at the same time can solve various problems at the same time. Those authors also stress the importance of this step to avoid problems of similar association and weak analogies, leading to a decline in diversity and originality of potential future design concepts based on the solution chosen. These techniques can help to meet multiple requirements that the project will respond to.

After identification of the natural system that satisfies the aims, achieves the goals or solves the problem under study, one should perform an analysis of the biological solution.

2.1.4. Step A4 – Analysis of the solution

Designers must now identify and break down the structures, components, processes and functions of the biological solution, related to the problem to solve. The issues addressed in this phase, allowing a better understanding of the functional, structural, morphological and organizational levels, can be tackled by reflecting about "what is the function?” (Junior et al., 2002). This understanding of various aspects of biological characteristics of the solution can help meet multiple requirements, including effectiveness at formal, structural, functional and organizational levels.

The functional decomposition performed in the step of defining the problem may be useful in order to relate each function or sub-function and requirement of the problem with the functions and features of the biological solution (Helms et al., 2009). Thus, the understanding of the solution will be easier. Therefore, the solution that is most relevant and feasible for the particular challenges of the project can be identified and extracted in the form of a neutral solution, which requires a maximum reduction of the structural and environmental constraints of Nature (Helms et al., 2009).

After extraction of the principles of the biological solution and according to the feasibility of implementation and the needs of the project, designers can develop ideas and concepts based on natural models, following the guidelines and principles obtained in the analysis steps of the biological solution (A4) and of the problem definition (A1). The following step is concerned with creative application of the principles and concepts generated.

2.1.5. Step C1 – Generation of concepts

For generation of ideas, designers must consider the factors that influence the effectiveness of the natural form in the solution, the factors that influence the effectiveness of the function, the effectiveness of organization or the effectiveness of communication (in accordance with the objectives of the project in question), trying to incorporate them as similarly and as faithfully as possible in the design process.

As a result of this stage, sketches and 3D models (either obtained by computer modelling and, or physical models) of the concepts developed are expected. In these concepts, besides details considering all technical and functional principles identified, analogous to the biological model, environmental aspects such as life-cycle analysis, raw material, energy and waste generated (both in the manufacturing and the life of the product), the manufacturing procedures, recyclability, reuse and biodegradation after the life of the product, and aspects of packaging and transportation thereof (Kindlein et al. 2003) should also be understood.

Moreover, in this respect Nature is assumed as the protagonist and source of inspiration, whether by requiring attention to ecological aspects of the project or by focusing on the availability of natural recyclable, reusable, renewable and biodegradable materials, which should also be considered at this stage.

As a result of the process of generating concepts one may obtain a set of alternative concepts, which perhaps are not all equally suitable as a proposed solution. In these cases it is desirable to perform an intermediate stage of evaluation of the multiple concepts, according to a structured approach, such as that proposed by Ulrich and Eppinger (2004).

After selection by formal assessment of the designed concepts it is essential to validate these against the requirements and goals set for the solution.

2.1.6. Step C2 – Validation

The validation step of this method is the process where the final concepts face the needs and requirements of the problem and where the gains brought about by bionics are assessed against a conventional solution of the project.

Accordingly, and based on the results, the information and the models obtained in the previous step enable the designer to link the specific requirements and objectives of the project with five goals to achieve (or as many as applicable) set out in this work and provided as guidelines for the corresponding validation process, shown in Table 3.

Goals to achieve	Validation process for specific purposes
Innovation of paradigm for performance features	- Conceptual analytical and illustrative images to prove the change. - The paradigm shift evidences vary depending on the type of paradigm in question (examples): - The organizational level - change from a model of centralized decision-making within the organization to a cooperative, distributed process, performed by multiple elements decision-making. - The technical level - the principle of operation, drive technology, the source of energy, among others.
Optimization of shape	- A comparative approach compared to a conventional product. Examples: - Reduction of material and weight - analysis from solid modelling. - Stability – Analysis of static centre of mass (vector mechanics). - Resistance to the maximum capacity - finite element method and test of prototypes. - Storage of objects - quantification of capacity or maximum capacity.
Satisfaction of multiple requirements	- Check objectively and as much as possible, the level that has been reached for each property implicit in each requirement. - Check if the resolution of conflicts between non-compatible properties was carried out on both sides achieving a compromise between the requirements in question.
Effectiveness of organization	- Comparison between two or more systems with the same function (including the proposed system), but with different methods of organization. - Take measured levels during effective operation (real or simulated) of systems (including the proposed system) such as execution time, energy expended, material resources, expenditures, or funds generated.
Effective communication	- Validation according to the level of communication in question: - Passive Communication (triggered by observation) - effectiveness may lie in the overlap between the meaning intended to be incorporated into the product or system by the designer and the signification readings of users or observers (empirical verification). - Active communication (process between a sender and receiver synchronously) - effectiveness evaluated from the overlap of verified posts from the transmitter to the receiver and their outcome in the receiver, which should be in accordance with what was intended by the transmitter (empirical verification)

Table 3. Aspects of validation of targets to be achieved in design processes making use of the bionic approach, with indication of specific applicable procedures.

According to the results of the validation process, there might be a need for further testing, making modifications or refinements to the models, and reassessment of the principles of the biological solution and the requirements of the problem through iterations between the steps of the method, in order to attain validation. In case of complete satisfaction, validating the results, one or more concepts can then move on to the detailing and finishing phase of the bionic design project.

2.1.7. Step C3 – Detail and finish

In the last phase of the project the considerations required for the type and purpose of project that is developing that would enable the company to place the product on the market are met. Analyses of technical, financial, environmental and market aspects are also useful for the success of a product. Technical drawings and detailed descriptions of all components of the project, descriptions of the materials used, descriptions of the process of manufacture, assembly, packaging, or instructions for use are typically conducted. It is also necessary in many cases to perform the construction of a scale prototype for display and presenting the product more realistically and assessing its feasibility. In the presentation and communication of the product, eco-marketing actions should also be considered in order to effectively convey the sustainable benefits to potential customers and consumers of the product (Camocho, 2010). The existence of monitoring activities at the end of the product development process, such as sustainability reports, checklists (eco-design checklists) that consider experiences and evaluate the product, identifying new needs, are equally relevant (Camocho, 2010).

2.2. Description of the methodology developed following the orientation from the solution to the problem (B)

Following the reverse path, the direction for the project in question from the observation of Nature and useful collection of possible solutions for future applications in projects, the first step is to identify the biological solution, progressing along the following steps shown and described below.

2.2.1. Step B1 – Identification of the bionic solution

At this stage, after the observation of natural phenomena has taken place, through aid from literature review or field research, potential solutions should be found with remarkable properties or characteristics, to be transferred for application to human problems. Subsequently, the greatest number of information concerning the identified solution is obtained to carry out the analysis of the solution.

2.2.2. Step B2 – Analysis of the solution

At this point of the design process, a number of factors is determined that enable perceiving the shape, structure, organization and functional principles of the solution. Thus, one must recognize the components or systems involved in the phenomenon under analysis, and identify the organization and morphological structure, assimilate the mechanisms, principles and levels of organization, understand how the environment influences these mechanisms, among other relevant aspects for the knowledge and analysis of the solution (Colombo, 2007).

The basic questions that must be tackled at this stage are the "why" and "how Nature works" and "what is the purpose of its form and structure" (Colombo, 2007). From this analysis, in schematic / functional notation mode, the designer can extract the principle or principles that motivate the fundamental solution.

2.2.3. Step B3 – Reformulation of the solution

The stage that follows relates to the reformulation of the solution, which aims to facilitate the search for human needs, in which the biological functions of the solution may be useful. For this purpose, with the functional principles extracted from the previous step, the designer must now deduct general and specific principles, in detail, and consider possible links between the biological and the mechanical behaviour.

After reformulation of the functional principles of the natural solution in terms of technical principles and functions, follows the search for a problem.

2.2.4. Step B4 – Search for a problem

While the search in the biological domain is restricted to a finite space of existing solutions developed by Nature, the search for a design problem can include not only some existing need but also an entirely new problem (Helms et al., 2009). The designer must thus, taking into account the data obtained during the reformulation of the solution, look for real problems that are unsolved or still have gaps, collect examples of existing solutions with the possibility of more effective and sustainable solution or identify emerging needs with yet no solutions, but that may be met with bionic considerations already identified, resulting in entirely new products. Once one has identified a potential problem related to the functional principles of biological phenomena, the next step will be drafting the design brief and its association principles.

2.2.5. Step B5 – Design brief and association principles

For a clear association between the systems and components of the biological solution and the functional aspects of the problem to be solved with bionic inspiration, this stage includes the development, identification and outline of the general and specific principles for the operation of the product. It is also essential to bring forward at this stage a list of requirements and restrictions for the product to develop, where the environmental and ecological variables are also to be included.

The fundamental objective of this step is to draw a parallel between the principles and requirements of the problem with the fundamental properties of the solution extracted from the analysis.

After understanding the analogies between the potential problem and the existing solution from the natural world, and with the aid of schematic notations, functional principles extracted from the solution and analysis of the principles and specific requirements of the problem, follows the step of developing ideas and concepts. This step is applicable in both orientations of the method.

2.2.6. Step C1 – Generation of concepts

The generation of concepts step, is common to the approach oriented from the problem to the solution and was described in section 2.15. The next phase of the method deals with the evaluation or validation of the concepts generated and is also applicable for the two orientations of the method.

2.2.7. Step C2 – Validation

According to the results of the validation process, there will be a need for further testing, modifications or refinements of the models, and reassessment of the principles of biological solution of the problem and the requirements for a new validation (see description for this step in section 2.1.6). Total satisfaction and validation of results, will enable to proceed with detailing and finishing the project.

2.2.8. Step C3 – Detail and finish

This step is common to both orientations of the developed method of analysis (see description in section 2.1.7).

It is a well-established fact that Nature is constantly learning, adapting and evolving. In a method for developing products, in particular, a bionic design process, it is beneficial to consider this teaching, making progressive drafts in successive stages of observation, problem definition, solutions analysis and validation. Thus it is important to note that even with the arrival of a drafted concept to the final stage of the method, there will always be the need to continue to improve the design and optimize the product.

2.3. Adequacy of the proposed method to support the satisfaction of the five goals focused

The genesis of the proposed method comes from a collection of methods retrieved from literature which seeks to reap the benefits of the several methods reviewed in the new combined method (and still looking as far as possible to overcome some of the shortcomings pointed out). Thus, based on subjective evaluation (and its justification) of the applicability of each of the five methods for focusing on the objectives (Versos and Coelho, 2011-a, 2011-b, 2010; Coelho and Versos, 2011, 2010), we present an analysis of the same objectives towards applicability of the proposed method.

2.3.1. Optimization of shape

Based on previous analysis (Coelho and Versos, 2011) it appears that only the method of spiral design (Biomimicry Institute, 2007) was deemed applicable to pursue this goal, with the justification for this classification attributed to the fact that it is an iterative method, explicitly, which favours systematic optimization. Since the characteristic of interaction is present in the proposed method in its two directions of analysis, it is deemed applicable to support achieving this goal.

2.3.2. Satisfaction of multiple requirements

In previous analyses, Coelho and Versos (2011) considered the Bio-inspired design method (Helms et al., 2009) as the only one of the reviewed methods applicable to support this objective (note that this is a problem-oriented approach). In the proposed method, this is considered in steps B3 (orientation from the solution to the problem) and A4 (direction from the problem to the solution), as this results from extracting from the constraints of the biological solution to make the most expeditious implementation of the principle of solution in another domain. However, these requirements are not explicitly considered after the transfer of the biological solution to the new field; considering this point, there are some shortcomings. The techniques for finding solutions, also presented in the Bio-inspired design method (Helms et al., 2009) for the selection of solutions through its various features solving several issues at the same time, also contribute to meeting this goal. In the orientation of analysis from the problem to the solution, the method developed, was considered contributing to the achievement of the satisfaction of multiple requirements in the project to be developed. The fulfilment of this goal can also be met through the consideration of environmental and ecological variables in the project, highlighted in two directions of analysis.

2.3.3. Innovation of paradigm for performance features

In previous analysis by Coelho and Versos (2011), all analyzed methods were considered applicable to provide support to achieve the objective of innovation of the paradigm for performance features. This is considered a key motivation for the proposal of each and every one of the methods previously scrutinized. It is achieved by the appearance across all the methods discussed of the processing of a biological solution so as to provide a solution to a problem inherent in a design concept. Since the proposed method considers this transformation (as in the passage from A1 to A4 and from B1 to B5) it is obvious that it satisfies this objective.

2.3.4. Effectiveness of organization

This goal was considered as fully supported through the use of the Aalborg method (oriented from the solution to the problem). The Aalborg method of analysis has achieved the category 'applicable' to achieving the goal of effectiveness of organization in view of the first stage of this method of analysis that, among other areas, focuses on the organization, structure and morphology of levels in the natural system. Given that these aspects are contemplated in both directions of analysis of the proposed method (A4 and B2), the classification of applicable is considered for this parameter for the case of the proposed bi-directional bionic design method.

2.3.5. Effective communication

Effective communication was considered a goal for which there is no support from existing methods (Coelho and Versos, 2011). Although one might consider, particularly in future work, giving support to achieve this objective, we chose not to follow this path in this work.

However, in the validation itinerary, considerations are integrated into the proposed method that are aimed at supporting the possibility of evaluating the effectiveness of communication achieved by using conventional methods to stimulate creativity. Thus, the developed method is considered applicable, albeit with gaps to be filled in the future, to support the goal of effective communication. However, for most situations, the method is applicable to support the achievement of the goal, but it cannot be achieved if it is not explicitly considered in the briefing that gives rise to the design project.

As a summary, Table 4 compares the applicability of the method developed in its two orientations of analysis, given the five key goals considered.

Goals / Direction of analysis	Optimization of shape	Satisfaction of multiple requirements	Innovation of paradigm for performance features	Effectiveness of organization	Effective communication
Orientation from the problem to the solution (A)	Applicable	Applicable	Applicable	Applicable	Applicable
Orientation from the solution to the problem (B)	Applicable	Applicable	Applicable	Applicable	Applicable with shortcomings

Table 4. Comparative analysis of the applicability of the bionic design method developed in its two orientations of analysis, given the five goals selected and considered representative of those applicable to design problems.

The development of a new methodology sought to meet the issues identified during previous study of existing methods. Steps are proposed so that the design method proposed is intended to address shortcomings in existing methods in the course of the analysis in view of their applicability to support the process to achieve five goals considered representative of the objectives pursued by those who follow a bionic approach to design. As such, we developed a descriptive method that, in addition to considering the two directions of analysis to support the validation and fulfilment of the objectives set, provides support for an iterative approach in conducting the project. It is thus meant to assist in the optimization of the results achieved with the use of a bionic approach. The method uses an approach which combines contributions of previously existing methods, which were valued by the analysis, and support of the goals listed (Versos and Coelho, 2011-a, 2011-b, 2010; Coelho and Versos, 2011, 2010). As can be seen by the comparison presented in Table 4 on the applicability of the support given to achieve the goals chosen by the proposed method (referred to in its two directions of orientation), the method supports the applicability for all combinations of goal and orientation. In addition, the proposed method achieved an increase in applicability in relation to previous methods in order to optimize and to satisfy many requirements in the orientation from the solution to the problem and for effectiveness of organization in the direction of the design process from the problem to the solution. We also considered other activities not anticipated in the methods reviewed in order to more fully support the objectives of optimizing the shape and satisfying multiple requirements. The purpose of communication effectiveness is still suffering from a lack of support for its complete satisfaction. Thus it is recommended that projects where this objective is sought, make use of other approaches described in the design literature to systematically encourage their satisfaction (e.g. Figueiredo and Coelho, 2010).

However, the proposed method while not supporting to the same degree the validation of the five objectives focused, supports validation efforts explicitly which is very distinctive of previous methods. Thus, even if not directly supporting the process leading to the satisfaction of all stated purposes, the use of this method, providing validation mechanisms, helps designers realize the level of satisfaction of each objective achieved in each iteration of the project. This assessment will assist the recognition of the need for measures to correct the detected deviations in light of the design brief objectives.

3. Examples of application of the bi-directonal method of bionic design

In order to enhance and complement the method developed, its practical application is essential. In this regard two design projects were developed that follow the method of bionic design created and presented in this chapter. This was intended not only to validate and prove its practical applicability, but also as a way to complement and in order to enhance the dissemination of the method. The deployment of the method used to guide the development of these projects is summarily shown in the following subsections, excluding steps C2 to C3. Step C1 concerns the validation stage of the method, and its content has previously been shown by Versos and Coelho (2011-a). The first design case concerns the process of design of a CD tower rack developed by the first author and following the proposed method (following the direction of analysis A—from design problem to bionic solution) with a solution inspired on the spider web. The second design example reported on, was developed starting from the elastic structures of Nature arriving at a quad-cycle with frame integrated suspension developed by the first author and following the proposed method (following direction of analysis B – from the bionic solution to the design problem).

3.1. Bionic tower for storing and holding CDs and DVDs

To consolidate and justify the method and solutions presented in this work a practical case study following the direction from the problem to the bionic solution was developed as example. The problem that has been proposed was to develop the design of a solution for bionic shelving for CDs, DVDs and books.

3.1.1. Step A1 – Problem definition

In a first step, and taking into account that the orientation of this project is initiated by identifying a problem that seeks a solution, key product requirements were established so as to define and specify the problem in question. These requirements stand in addition to the basic function of versatile storage of CDs and DVDs in their covers or books (1), in the stability against dynamic disturbances (2), and greater gripping of objects stored (3), all this as opposed to the conventional solution. Beyond these requirements other goals were still considered, specifically: increased lightness (4) against the conventional solution, ease of use through a good positioning of the spines of the CDs, DVDs and books with a view to readability (5) and a positive perception by the user in a pleasant and appealing way (6) allowing an aesthetic interest for the product to development. The last requirement, also related to communication objectives of the subject, relates to the transmission of a message an avant-garde, creative and youthful spirit (7) by the artefact. The final product should target a diverse audience in order to meet the needs and tastes of people of both genders and all ages.

Requirements (2), (4) and (5) contribute to the goal of optimizing the shape. Requirements (5), (6) and (7) contribute to the goal of effective communication. With respect to satisfying multiple requirements, in this project, this goal is achieved by the joint consideration of the objectives (1), (2), (3), (4), (5) and (6). Regarding the goal of the effectiveness of organization, this is contributed to by objective (1). The goal of paradigm innovation of performance features is a goal that does not lend binding itself to targets, and will be affected by the bionic design project results as a whole.

In order to synthesize the requirements and constraints of the problem and help the subsequent evaluation of new solutions, through satisfaction of the criteria and targets established, a Table of requirements and specifications of the problem was drawn up (Table 5).

Project Requirements	**Goal to Achieve**
(1) Enable storage with versatility of CDs, DVDs in their covers or books	- Effectiveness of organization
(2) Increased stability before a dynamic disturbance when compared to a conventional solution	- Shape Optimising
(3) Greater grasp of objects stored against a conventional solution	- Innovation of paradigm for performance features
(4) Increased lightness when compared to the conventional solution	- Shape Optimizing
(5) Proper positioning of the spines (CDs, DVDs and books) with a view to good readability	- Shape Optimising - Effectiveness of communication
(6) pleasant and appealing Form that allows the user to develop an aesthetic interest in the product	- Effectiveness of communication
(7) Convey a message of avant-garde, creative and youthful spirit	- Effectiveness of communication
Sustainability Requirements	**Goal to Achieve**
Reducing the environmental impact of materials: - Materials that are recyclable at the end of the product lifecycle - Biodegradable materials	
Ease of maintenance and repair	- Effectiveness of organization
Low weight of the final product's packaging for transportation	- Shape Optimising

Table 5. List of requirements and goals of the project to achieve the tower of CDs and DVDs, with details of the requirements to respect sustainable. Note that all requirements, including those of sustainable character, contribute to the goal of satisfying multiple requirements.

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3.1.2. Step A2 – Reformulation of the problem

To facilitate the process of looking into the nature of biological solutions that meet the requirements of the problem, the next step was to revise the functions present in the project requirements in terms of biology and in general. Thus, a few threads of a functional nature were obtained that serve as guidance for the following step (Table 6).

Requirements	Reformulation of the requirement in terms of functions performed in Nature
Greater grasping and securing of the objects stored	-Natural solutions that capture or immobilize certain bodies Natural systems-used for the purpose of protecting organisms
Greater stability in response to dynamic disturbances	-Natural features enabling not suffering falls or impacts and resisting loads -Organisms in Nature with dimensions and morphology seemingly fragile, but with great resilience
Lightness	-Organisms, property or natural materials that are lightweight, without neglecting resistance
Reducing the environmental impact of materials	-Natural materials using renewable and biodegradable substances

Table 6. Reformulation of project requirements for CDs and DVDs tower in terms of features and functions performed by Nature.

3.1.3. Step A3 – Solution selection

Upon revising the requirements for functions and features present in Nature we sought to find, through literature review and field observations, biological solutions that best solve or respond to the topics defined. With respect to solutions that capture or immobilize natural bodies and certain natural systems used in order to protect organisms (for the requirement of greater gripping of objects) the solutions consist of cobwebs and cocoons, respectively. In addition to recognizing a similar approach between the functions held by this biological phenomenon, the cobwebs are also lighter and stronger, also responding to the requirement of lightness.

For the requirement of stability to a dynamic disturbance, taking into account the natural features that allow not suffering falls or impacts and resist efforts, organisms identified in Nature seemingly fragile, but with great resilience, were the branches of trees as an inspiring solution. Although often subject to strict conditions as the wind, and apparently fragile with modest thicknesses but reaching great length, the branches of trees show great resistance.

3.1.4. Step A4 – Analysis of the solution

The construction of the spider web, extremely lightweight and very durable - five times stronger than steel for the same cross section, can stretch more than four times its original length - aims to serve as a passive trap to "capture" insects that intersect with it, subsequently serving to feed the spider. In addition to this primary function, the cobwebs have also functionality provide support and shelter the eggs of its creator (Yahia, 2001).

The fundamental principles of the extracted biological solution (spider web) are the elastic threads, which when multiplied and combined in a particular organization, allow one to create a means of support and enclosure (principle associated with the function of gripping objects) quite sturdy and lightweight (associating the requirement for greater lightness, without loss of strength).

With respect to the second biological solution found, trees, specifically the branches, are often subject to adverse weather conditions (such as wind), bearing, despite the apparent thickness and fragility of the great lengths of their structures, high loads. This ability comes from the remarkable elasticity of the fibres in their material, tolerating movement, flexion and extension of the branches. The principle of the solution to be harvested in order to meet the requirement and functions of greater product stability is the availability of components with elastic properties which allow flexibility of the structure in case of disturbances.

3.1.5. Step C1 – Generation of concepts

After extraction of the principles of biological solutions identified the following two concepts and ideas were developed (Figures 1 and 2).

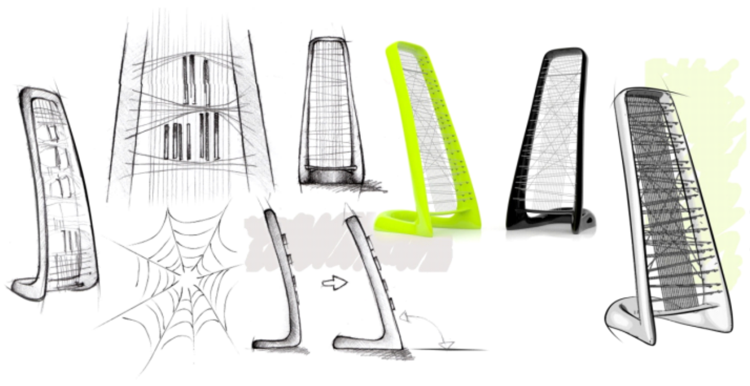

Figure 1. Sketches for the generation of the tower concept for CDS and DVDs - bionic 1.

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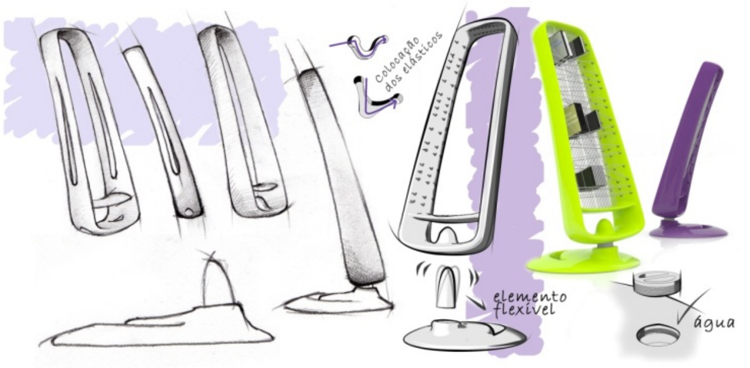

Figure 2. Sketches for the generation of the tower concept for CDS and DVDs - bionic 2.

A system for storing CDs and DVDs in their covers structured by elastic threads, was devised, which, like the capacity of webs of silk, allows grasping objects while based on a new archetype of dematerialized ordinary shelves so as to result in a lighter solution, both visually and physically. The system of elastic threads developed visible in Figure 3 was disposed vertically and arranged - for the purpose of guiding the objects in a fixed position to organize the storage and readability of the spines - having the task of gripping objects and spatial organization.

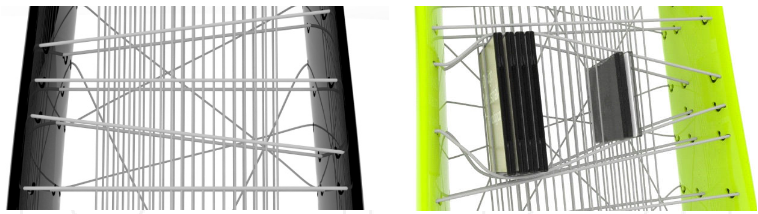

Figure 3. Guidance System of elastic threads of the towers and working sample and storage.

The first concept developed (Figure 1) for the bionic tower structure consists of a single compounding format of the tower and "webs" support system. The elastic threads are laid with pre-tensioning in holes in the structure itself, prepared for easy manual assembly or replacement of the elastics if required. A second "web" of elastic threads at the rear of tower structure was also used in order to ensure the fixing of the objects preventing them from falling. The structure of this solution was purposefully designed with a slope such as the positioning of the elastic threads horizontally and across, so as to facilitate the reading of the spines of the objects to be placed. The end result of this concept can be seen in Figure 4.

Figure 4. Representing the final appearance of bionic tower 1.

Due to the need to use some strength to place the objects in the "warp" system and because of susceptibility to dynamic disturbances in the structure of the tower, there is a need to increase the stability thereof. From the biological solution already analyzed (flexibility of the branches of trees) we developed the concept for the second tower (Figure 2). This concept, along with a light support structure (frame) of the "web" system, has a separate base connected to the frame via a third element consisting of a material with elastic properties, to ensure the flexibility of the structure. In case of a disturbance, it will provide greater stability to the tower, which will behave just as a branch of a tree, and (Fig. 5).

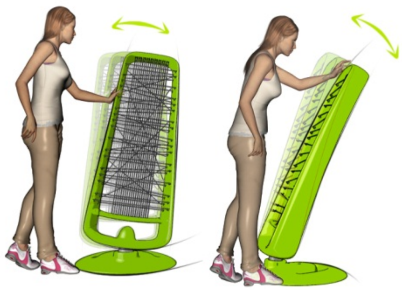

Figure 5. Demonstration of the functionality of the joint at the base of tower 2, responding to user interaction movement, increasing the bionic nature of the solution for its dynamism.

For this resilient member, its function is to store strain energy when the user intentional tilts the tower (Fig. 5) so that it may be positioned in slope for the convenience of the user and so that the insertion force for a new object in the tower is reflected in the same inclination temporarily. The elasticity of this element is given by the properties of the elastomer selected from natural origins (similar to that used in elastic filaments selected for the concept presented in the following section). To create additional rigidity a component arranged vertically inside this element is incorporated, considering the feasibility of using a bamboo cane segment. This process of selection and sizing, beyond the scope of the work presented here, will bring the possibility of gauging the dimensions of the components of this element and its proportion in future tests, with a full-scale working prototype.

Apart from this enhanced property, it is also possible to introduce sand or water inside the tower base, in order to increase the mass of this element, contributing to the enhancement of stability (displacement of the centre of mass of the tower) without compromising the size and low weight of the tower in transportation or distribution stages of the product.

Figure 6 represents the final look of the bionic tower 2, with different chromatic versions.

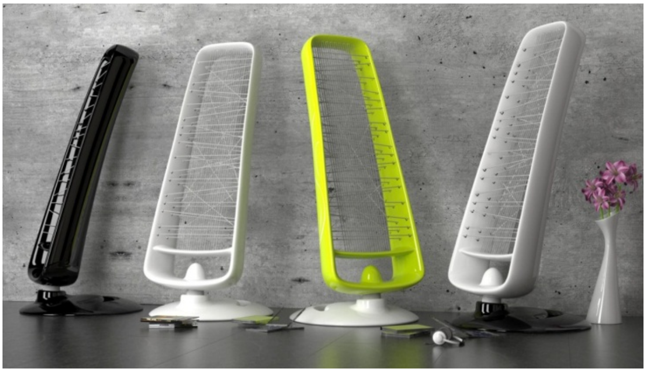

Figure 6. Representing the final appearance and colour studies for bionic tower 2.

3.2. Optimization of structures according to the rules of nature

Through observations of Nature and literature searches, it is possible to gather information about possible biological solutions useful for application in projects. This is based on the analysis of natural structures secrets for lightness, durability and resistance to various efforts or conditions and finding ways to link new solutions to existing or novel human needs to the solutions and rules of Nature.

3.2.1. Step B1 – Solution identification

In Nature there are numerous structures that grow and develop in order to adapt to the conditions to which they are subject. In examples present either in flora and fauna, there are small structural solutions which represent much of the secret to optimize resistance. In trees, for example one may find technical solutions to increase the resistance of structures and efforts to prevent fragility. Other structures such as bones or skeletons are also examples of inspiration because they demonstrate being as light as possible and at the same time as strong and resistant as required. in the analysis of the solutions identified, the book “Secret Design Rules of Nature", by Mattheck (2007) was considered as a reference.

3.2.2. Step B2 – Analysis of the solution

According to Mattheck (2007), observing the teachings of the structures and growth of trees can solve various problems related to efficiency of formal structures, or to eliminate or reduce the presence of cracks caused by accumulations of stresses (the reason for the ruin of a structure). According to the author, trees develop in order to strengthen the weaker areas of their structures. One of the main examples is how the base of the trunks develop in order to sustain the tree and the stresses to which it is subjected. The trunks develop more zones of connection to the ground, especially in directions exposed to the wind in order to reinforce the regions of greatest tension and avoid cracks (Mattheck, 2007). The branches and trunks of smaller cross-sections also demonstrate great resistance to impacts and dynamic forces through their flexible and elastic properties. The principle used here, as in all organisms is Nature, is of adaptation to the environment and surrounding conditions. In contrast, man-made mechanisms tend to resist and counteract adversity.

The same author discloses a method (tensile triangles) based on the growth of tree structures, to reduce the accumulation of stresses at weak points (cracks susceptible to) and to counteract potential sites of fracture. The method consists in the introduction of a square triangle, with the two acute angles of 45 degrees, symmetrically about the corner of the structure. The introduction of this triangle creates new fragile zones, susceptible to cracks, though less dangerous than the initial one. A new triangle is inserted symmetrically to the corners of the triangle resulting from the first approach, and so on to reduce the angle of fragile zones. According to the author, usually three triangles in the desired direction are sufficient. This method is similar to what the CAO (Computer Aided Optimization) method performs. The representation of this optimization system is observable in many natural structures, as for example in trees. This method can also be used in order to eliminate unused areas and components subject to excessive stresses, reducing the cross-sectional area of the component and providing optimal distribution of the stresses to a minimum area, avoiding wastage of material and reducing the weight and volume of structures. These features of formal optimization are also observed in the structures of bones or skeletons and are applied by the SKO (soft kill option) method.

3.2.3. Step B3 – Reformulation of the solution

Trees are elastic structures; such elasticity is desirable in artefacts used by man, especially in structures that are subject to dynamic loading. The solutions of optimization and adaptation to the environment that natural bodies present may contribute to the structural effectiveness of a product in order to adapt this same structure, subjected to stresses and dynamic conditions, with better results. From another perspective, the optimization and formal characteristics observed in skeletal bones (mild, simple and resistant) may contribute to the reduction of the cross-sectional overall area of a structure and hence to its dimensions and its weight without compromising strength and resistance to the loads endured.

3.2.4. Step B4 – Problem searching

Powered vehicles and propulsion for human endeavours necessarily imply a lightweight and practical manner to enable and facilitate human activity. For sites with flat terrain and the difficulty of rapid movement of these vehicles is reduced, justifying the existence of many bicycles, skates, skateboards, scooters and even tricycles, among others. In most rugged and mountainous terrain rolling on these vehicles is difficult, making it uncomfortable for the user and also causing damage to structures that are not prepared for the conditions. An existing solution, present in mountain bikes, is strengthening and equipping the structure with mechanical suspension components that allow control of the oscillations. Such a solution increases the costs of the vehicle and does not solve in a complete manner other associated problems.

For those who need to perform usual activities in hilly terrain, as evidenced in activities such as monitoring forests, difficulties are felt related to the actual movement or transport of other equipment necessary for the practice of the actual tasks. The bicycle is a vehicle more accessible for these functions but is revealed impractical in most scenarios meandering lack of stability, because of having only two wheels. The lack of comfort in travelling is another of these problems.

3.2.5. Step B5 – Design brief and association principles

According to the needs and problems identified in the previous step, requirements were established to guide the design of a vehicle powered by human effort in mountainous terrain. Thus, as a first requirement, it is desired to design a vehicle that allows access to rough roads (1) with improved comfort and stability when compared to a bicycle. This requirement is joined by the design of a damping system (2) of oscillations and impacts without use of a mechanical components suspension. The vehicle use should be sufficiently mild so as to reduce the effort required to operate and to facilitate human activity (3). The final product should also allow adaptation of fittings (4) for transport of tools to support the development of other activity by the user.

For the goal of optimizing the shape of the required object contribute to requirements (1) and (3), while the latter requirement (4) goes against the goal of organizational effectiveness. In what concerns innovation of the paradigm inherent to the performance of functions, requirement (2) directly contributes to this and is to be achieved with the proposed bionic design. The joint consideration of all requirements aims satisfying multiple requirements.

In order to establish a relation between the conditions and the properties of the problem, in analyzing the extracted fundamental solution, Table 7 was prepared, an association between the early solution and the extracted requirements inherent the problem and the identification of the environmental and ecological variables desired.

Principles derived from the solution	Project requirements
-Structures with elastic properties, as tree structures' analogy -Solutions with formal optimization and adaptation to the environment where trees are	(1) Access to rustic trails with greater comfort and stability
-Structures with elastic properties, as analogy to the structures of the trees	(2) System for damping of oscillations and impacts, without the use of mechanical suspension components
-Optimization of form through formal observation of forms and properties of skeletons and bones (light and strong)	(3) Lightness of product to reduce the effort required to operate it
	(4) Enable fitting of accessories for transportation
Environmental and ecological variables	
Reducing the environmental impact of materials:	
Materials that are recyclable at the end of product life cycle	
Biodegradable materials	

Table 7. Association between the principles extracted from the solution and the project requirements, identifying the environmental and ecological aspects to be respected.

3.2.6. Step C1 – Generating concepts

In the generating concepts phase, creative ideas and principles extracted from the solution and the project requirements, associated in the previous step, were developed and considered. Thus, the development of a structural form was sought based on the solutions and methods shown by Mattheck (2007) and in accordance with the teachings of the structures of trees and skeletons.

In order to provide greater stability and effectiveness in hilly and rough terrain, a four-wheeled vehicle for one person (see Figure 7), designated Biocross was conceived through a single structure and continuous lines, resembling the skeleton of an animal. The design of this object followed the steps in the methodology proposed in this chapter (steps B and C).

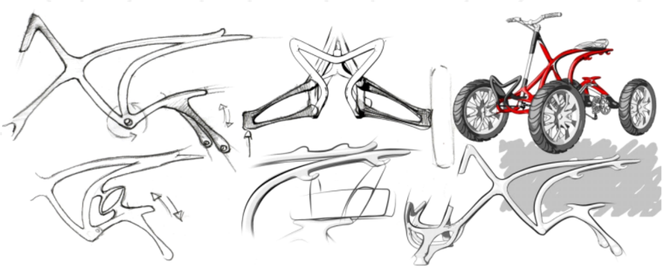

Figure 7. Sketches illustrating concepts generated for a bionic pedals vehicle and representation of a perspective drawn from the concept developed.

Figure 8 shows the method bionic optimization of structures using the approach proposed by triangles voltage Mattheck (2007), adopted in the design of the vehicle structure, which aims to reduce and eliminate critical areas of accumulation of tensions, providing Optimum reduction material.

Figure 8. Formal optimization method used in the design of the bionic pedal vehicle structure.

The four-wheel connection structure itself is tapered to allow zones of greater flexibility, thus dampening the oscillations caused by terrain (Figure 9). The purpose here, as in trees or any body of Nature, is to allow the structure to adapt to environmental conditions to which it is subjected, unlike conventional mechanical components (damper and spring) that seek to counteract and withstand the irregularities of the terrain.

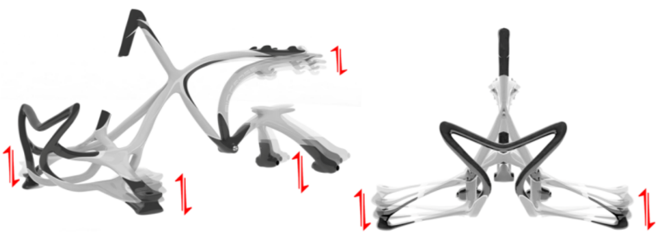

Figure 9. Representation of the effect provided by the suspension of the bionic pedals vehicle.

In order to ensure greater comfort and convenience to the user, a seat was built larger than those of ordinary bicycles. At the border of the front structure of the vehicle protrudes a protective guard thereto. In order to meet the requirement which calls for adjustment accessories for carrying utensils, at the rear of the structure itself, support bases and hooks for fastening accessories were added. All other components of the vehicle were considered standard, rendered through CAD modelling conducted for the purpose of displaying the full product (Figure 10) and perform solid mass tests.

Figure 10. Complete visual representation of the vehicle bionic developed with two chromatic versions of the Biocross bionic pedals vehicle.

Responding to the desired requirement that calls for reducing the environmental impact of the materials used bio-polymer (PLA) Ingeo Biopolymer 3251 was selected, which is also used in the design of the first bionic project described in this chapter.

4. Concluding remarks

The need for evaluation and validation during the development of bionic design projects enabling to measure product success in meeting efficiency targets and proposed requirements, was one of the evident missing features of previously existing methodologies for bionic design and which were met with the proposed methodology. Besides these aspects, the proposed method is also intended to support an iterative approach in conducting design projects in order to achieve optimal results and correct the detected deviations meeting the proposed objectives and needs. Implementation of the proposed method in practice aims its validation and also confirmation of the gains introduced in projects that follow the methodology for the process of design with inspiration taken from Nature. This is explicit from the results obtained during the two projects, which in addition to validate the method, serve as a complement to present the method.

Bionic design, a discipline capable of enriching projects with gains in efficiency, aesthetics and sustainability and with a wide margin for improvement and with a whole world where inspiration can be reaped from, will certainly bring benefits to designers in the future development of their concepts and their research. One of the studies included in this theme that could be accomplished in the future, with the objective of its development and expansion, would be an empirical study made by surveying designers in businesses that would allow identifying the actors who make use of the bionic methodology, principles and approach in everyday professional life. With the same objective, the application of a methodology for comparative analysis of the gains brought by bionics to a wide range of products would be equally interesting. It is also important to note that the method presented in this work, like any other, is not considered perfect or timeless. The evolution of scientific and biological knowledge, emerging technologies and the principles of sustainability provide new insights and new creative processes and designs. The design method should therefore be seen as a process of constant improvement, optimization and evolution – as in Nature.

Acknowledgement

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