AN INTEGRATED WORKFLOW OF BIOMIMETIC DESIGN, MATERIAL SELECTION AND COMPUTER AIDED ENGINEERING

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ABSTRACT: This study is aiming to showcase a 7-step procedure which illustrates the implementation of biomimetic concepts in product design, where nature acts as a source of inspiration and innovation. This research suggests a workflow, where specialized computational tools and methodologies are combined having as an objective the optimization of a design considering its environmental impact. This obviously relates to material selection, production techniques as well as geometric characteristics, structure and function of a product. The theoretical concept of this 7-step procedure is validated with a case study, the design and analysis of a furniture piece for outdoor spaces, which seeks inspiration in the morphology of scorpions and serves as an example for demonstrating the suggested workflow.
KEY WORDS: biomimicry, material selection, CAE, product design, optimization

1 INTRODUCTION

Designers have always looked at nature for inspiration and innovation. Natural structures have been optimized through millions of cycles of evolutionary development and therefore they constitute a great source of information and knowledge for engineers. The design approach of imitating (from Greek mimesis) the models, systems and elements of nature in order to solve complex human problems is known as biomimicry of biomimetics (Benyus, 1997). Regardless of the face that the history of biomimicry dates back to the beginnings of human civilization, initially humans would copy the shape and morphology successful natural formations, however only in the recent years it has been established as a systematic way to analyze existing forms employing computational tools in order to extract design principles from nature, in an attempt to address the generalized need for sustainability and efficiency in product design (Kyratsis et al., 2014; Kyratsis et al., 2015).

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2 SUSTAINABILITY AND LIFE CYCLE ASSESSMENT

Sustainable development is defined as the one that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al., 1987; Pedersen, 2007). Sustainability depends upon three interrelated factors (economic, environmental and social), which in several cases may result in conflicting design parameters. The aim of sustainable development is to attain interaction and balance among these factors with the objective to meet both social and economic needs, while protecting and preserving natural resources for future generations and securing the well-being of the environment and ecosystem on which life depends (Adams, 2006; Versos and Coelho 2011a and b; Kyratsis et al., 2012).

With the intention of eliminating the negative environmental impact and satisfy all three aspects of sustainability, the Life-Cycle Assessment (LCA) method was used for the environmental assessment of the proposed design for the chaise longue. LCA is a method for the quantitative analysis and evaluation of the environmental impact of a product throughout its entire lifecycle – from the initial ideation phases till the recycling of the product, including all intermediate stages of the product's lifespan. Environmental impact is mainly associated to air pollutant emissions and consumption of resources, both of which have hazardous long term implications, contributing to climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use and noise (Efkolidis et al., 2015).

LCA is a decision support system for designers and engineers, which calculates indicators of potential environmental impacts and evaluates possible alternatives aiming at the improvement of the product, pinpointing ways and methods for pollution prevention and reduced resource consumption. For the case study presented in this paper, the LCA method was implemented using the Solidworks Sustainability^{TM} LCA tool.

3 THE PROPOSED METHODOLOGY

Departing from a biomimetic design approach and considering the importance of sustainability and requirement for environmentally friendly design solutions, a methodology was developed, to systematize the abstraction of knowledge from nature and implement it in engineering applications. The aim is to utilize successful design from nature, learning, analyzing and replicating a particular characteristic or mechanism of a biological system and adapting it for the development of a new product, therefore addressing customer needs through a biomimetic approach.

The bibliography reveals that there are two major trends in biomimicry as a design process: a) solution driven, where an interesting biological phenomenon or mechanism inspires the search for potential applications, adapting it in the development of a new product, b) problem driven, where the identification of a given problem stimulates the search for biological mechanisms that could facilitate the solution of the problem (Goel et al., 2014).

The research presented here falls in the category of solution driven methodologies and having as an objective the design and developments of a product which is at the same time sustainable and eco-friendly. Current technological advancements and state-of-the-art computational tools, CAD and material selection systems have been of crucial importance and defined to a great extend the workflow of the suggested methodology, providing the necessary tools for validating the conceptual model. Figure 1 illustrates the 7 steps of the methodological framework.

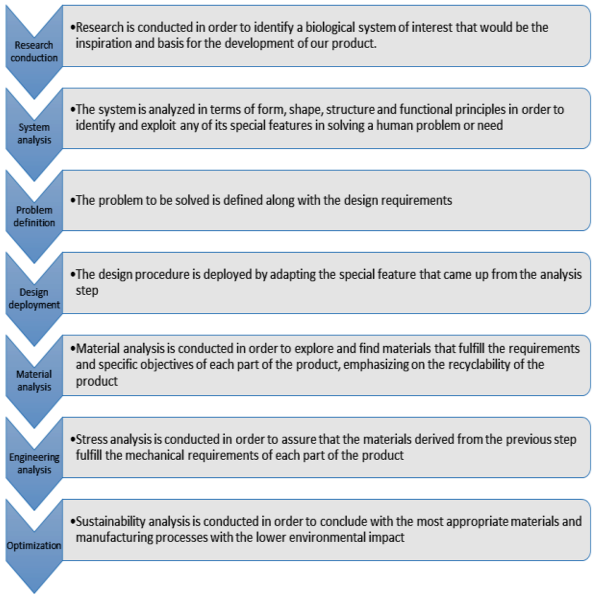


Figure 1. The 7 steps of the proposed methodology

3.1 Research

The workflow is initiated by a preliminary research into biological systems in order to identify successful design solutions, shapes, mechanisms, or other special properties and features that could be of use for contemporary engineering. A biological system is selected in the grounds of innovative design, inspiring therefore the designer for the development of a new product. In this case the biomimetic reference was the scorpion, due to its shape, modularity, and other reasons discussed in the analysis of the system.

3.2 System analysis

Following the identification of a system as a biomimetic reference, the following stage seeks to investigate, comprehend and analyze the morphology of the scorpion with regards to form, shape, structure and function. Scorpions belong to the class of arachnids, which falls into the broader category of Arthropoda. They have eight legs and their main and most recognizable characteristic is the pair of grasping pedipalps and the narrow, segmented tail with its venomous stinger, which is curved forward over the back of the body. Abstracting geometric principles, this stage usually involves conceptualization, sketching and rough visualization of ideas. The features were translated into geometrical principles. The sketches already embed design ideas, and guide further decisions on the product's development. This process helps the designer to identify whether the examined biomimetic principles could be implemented for the development of product of daily use.

3.3 Problem definition

Departing from the shape of the tail, it is seen that the segmentation, and reduction in diameter leads to lightness towards the tip of the tail, the tail is at the same time stiff and crustaceous (outer layer) while it permits movement and responsiveness. A possible implementation of the above geometric characteristics is the design of an adaptive furniture piece, that is curved forward in a similar fashion providing areas of shadow when needed. The shape inspired the development of a design of a sunbed that allows the body to be exposed to solar UV radiation while it protects the head, casting shadow only where needed. Therefore the concept that emerged was the design of a chaise lounge that implements the curved and segmented shape of the scorpion's tail, adapting a shading device at the tip of its backrest. In addition to the morphological reference, a series of design requirements were considered (i.e. outdoor use, lightweight, modular system, minimal design).

3.4 Design deployment

For the development of the design the following criteria were taken into consideration: user population (mainly young adults excluding children), product size (95% of the potential customers). Based on these design parameters and using the form of the scorpion as a morphological reference, the initial stages of the schematic design of the chaise lounge's frame were developed.

Table 1. The design requirements of the chaise longue's components

	FRAME	LEG
FUNCTION	Light and stiff frame	Light and stiff beam
OBJECTIVE	Minimize the mass, m, of the frame	Minimize the mass, m, of the leg
CONSTRAINTS	a. Length, L (specified)	a. Length, L (specified)
	b. Bending stiffness, S (specified)	b. Bending stiffness, S (specified)
	c. Fracture Toughness, $K_{IC} > 4.5$ MPa·m$^{1/2}$	c. Fracture Toughness, $K_{IC} > 15$ MPa·m$^{1/2}$
	d. Cost, $C_m < 5$ €/kg	d. Cost, $C_m < 5$ €/kg
	e. Recyclable	e. Recyclable
FREE VARIABLES	Frame thickness, t	Section Area, A

3.5 Material analysis

Engineering materials are categorized in the following six families: metal, polymers, elastomers, ceramics, glass, and hybrids. The members of each family have certain features in common (e.g. similar properties, processing routes, etc.) and often similar applications. Additionally, each material has particular attributes (density, strength, cost, etc.). Each design brief prioritizes different requirements and profiles (e.g. high strength, low density, modest cost, etc.). Therefore, the aim is not to depict a particular material but rather to set a certain profile of properties. For the scope of this analysis, the frame of the chaise lounge will be simplified and represented as a panel loaded in bending, while the leg will be considered a beam also loaded in bending. Hence, both components require certain amount of strength and stiffness to accommodate compressive loads and bending moments without failure and without compromising the requirement for lightness and simplicity.

The translation of the design requirements of the two components is summarized in Table 1. In order to select the appropriate materials, it has been crucial not only to meet the aforementioned design requirements, but also to maximize the product's performance. Two material property charts were examined with the use of the CES EduPack^{TM} software i.e. a chart of Young's modulus against density and a chart of fracture toughness against price (Figure 2). The materials that fulfilled the design requirements for each component were: a) for the frame: polypropylene–PP (index 0.00269), polyethylene terephthalate-PET (index 0.00112) and Polyvinylchloride-PVC (index 0.001), b) for the legs: Cast Al-alloys (index 0.00332), Age-hardening wrought Al-alloys (index (0.00319), Non age-hardening wrought Al-alloys (0.00311).

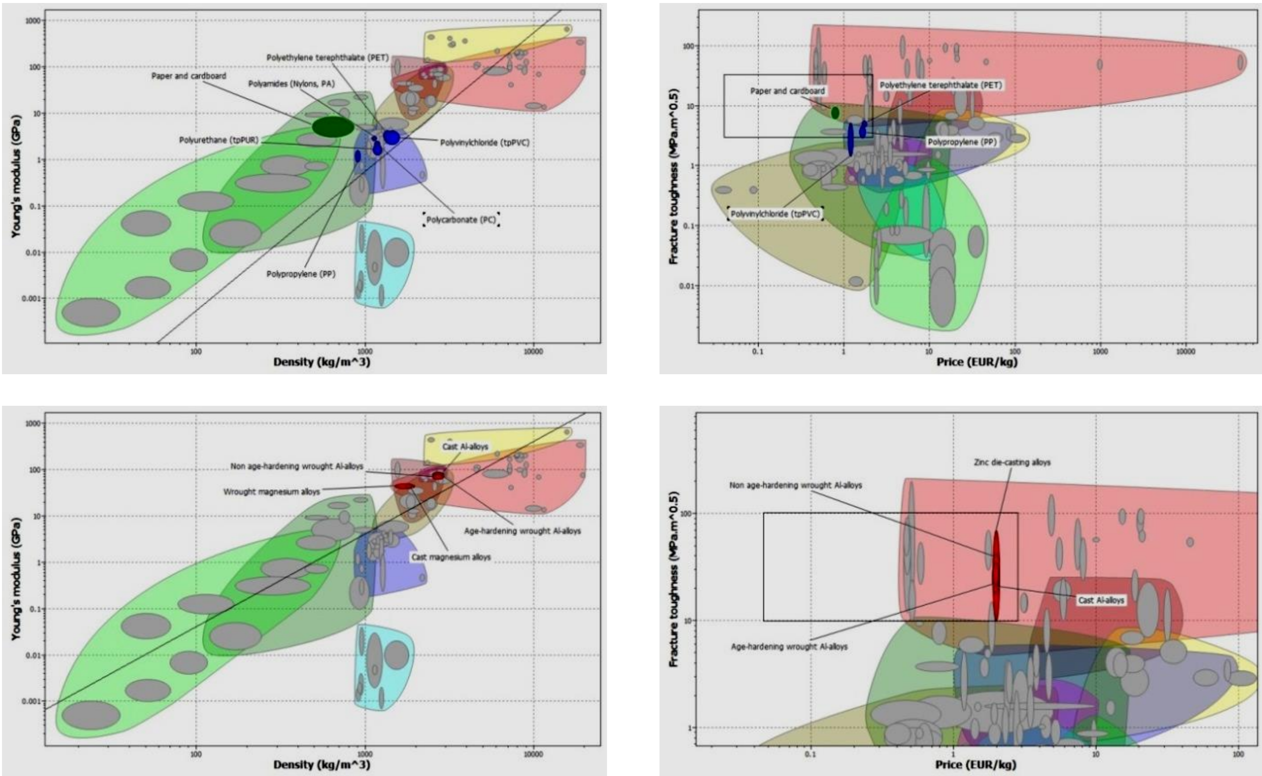


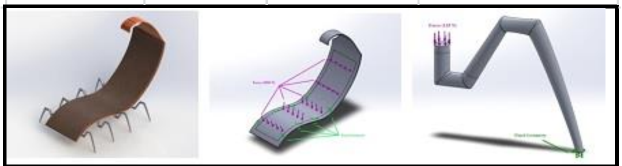
Figure 2. Material selection with CES EduPack^{TM}

3.6 Engineering Analysis

This step was to assure that the chosen materials meet the mechanical requirements of the design. This was implemented using the Finite Element Method (FEM – figure 3). For the scope of this study, each component of the chaise lounge was examined separately. Thus, stress analysis was carried out for all 3 materials that derived from the material selection phase. The materials examined for the frame were: a) Polypropylene (PP), b) Polyethylene terephthalate (PET) and c) Polyvinylchloride (PVC). The materials examined for the legs were: a) Cast Aluminum alloys, b) Age-hardening wrought Aluminum alloys and c) Non age-hardening wrought Aluminum alloys.

3.7 Environmental Impact Assessment:

In this last step the materials derived from the material selection phase along with their corresponding manufacturing processes were evaluated and compared regarding their environmental impact during the entire lifecycle of the product. The objective of this phase was to reach a final decision and select those materials that attribute to the design the optimum



Frame	Mass (kg)	V.M. Stress Max (Mpa)	Displacement Max (mm)
PP	17.030	9.27	115.17
PET	27.171	20.01	87.35
PVC	24.875	9.78	55.96

Legs	Mass (Kg)	V.M. Stress Max (Mpa)	Displacement Max (mm)
Cast-Al	0.836	160.68	3.52
Age-hard Al	0.836	160.68	3.92
Non Age-hard Al	0.836	160.68	4.36

Figure 3. FEM implementation

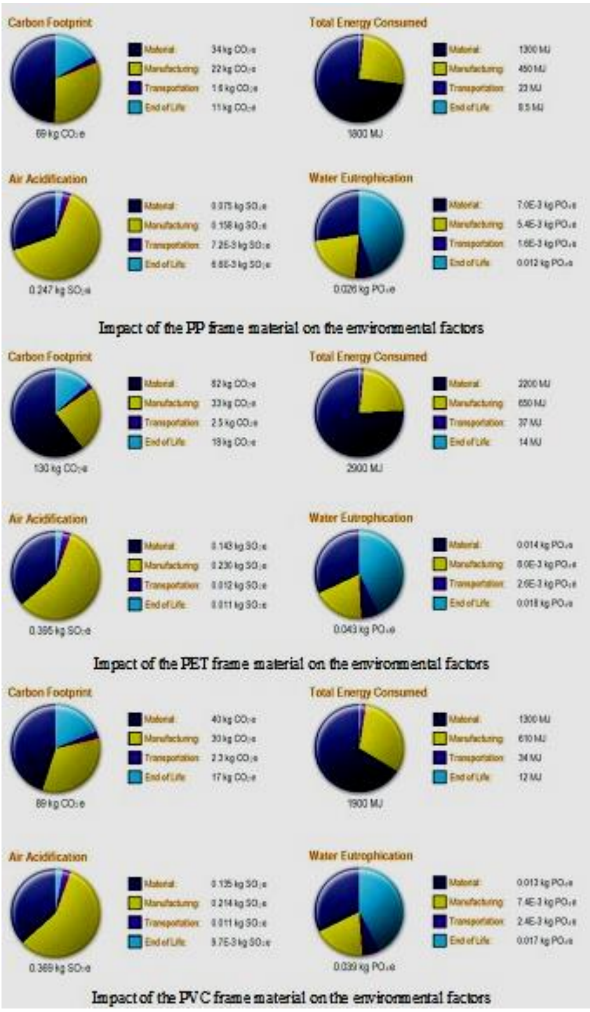


Figure 4. Frame's materials impact on the environmental

characteristics and performance with regards to both their mechanical characteristics as well as their sustainability and eco-friendliness. The analysis and evaluation of the environmental impact was carried forward with the use of Solidworks Sustainability™ tool, which employs the Life Cycle Assessment (LCA) method.

The data used in the Sustainability™ module are based on the GaBi™ software (PE International's database). The analysis was conducted in two stages. In the first stage, the software gathers specific environmental impacts for each component of the life cycle inventory and in the second stage, the impact of the four environmental indicators are calculated (Carbon footprint, Energy consumption, Air acidification, Water Eutrophication).

For the analysis of the present study the comparison was made assuming that the place of production and use is Europe, the mode of transportation is by truck for an average of 1900 km and the product's lifetime is 10 years. The manufacturing process selected for the production of the frame is injection molding and for the production of the legs is die casting. Additionally, in the case of the leg three different types of materials were selected out of a wide range that fall into the categories of the cast aluminum alloys derived from the material selection phase. The materials selected for the performance of the analysis were: a) 201.0-T6, b) 356.0-T6, c) C355.0-T61.

Figures 4 and 5 present the results of the evaluation procedure for each material and manufacturing process based on the four environmental indicators for each component separately of the frame.

Comparing the results in the charts (figure 4) and in figure 5, polypropylene (PP) is the most suitable material for the production of the frame since it meets the mechanical requirements for the product and additionally it is lightweight. At the same time, it has the lowest environmental impact. As far as the production of the legs is concerned, the three materials present either no or very small differences with regards to their mechanical characteristics. Thus, the choice was made on the basis of their environmental impact. The material with the lowest impact is the Cast Aluminum alloy 356.0-T6 and that was the final selection for the production of the legs.

4 CONCLUDING REMARKS

Using this case study as a reference, the research aims to propose a methodology and contribute to the discipline of product design providing the conceptual framework for a sustainable design workflow that implements and capitalizes biomimetic principles. The adoption of such methodology by contemporary product designers will result in the increase of the amount of sustainable design projects which will in turn affect the environment and the quality of life on earth. The aim of this methodology is to provide a roadmap for product designers and motivate engineers to look at nature for inspiration and innovation. The utilization of biomimetic references for the design and development of a product yields innovation, while at the same time, the optimization of a product with regards to its environmental impact through contemporary computational tools leads to the development of sustainable and efficient products and processes.

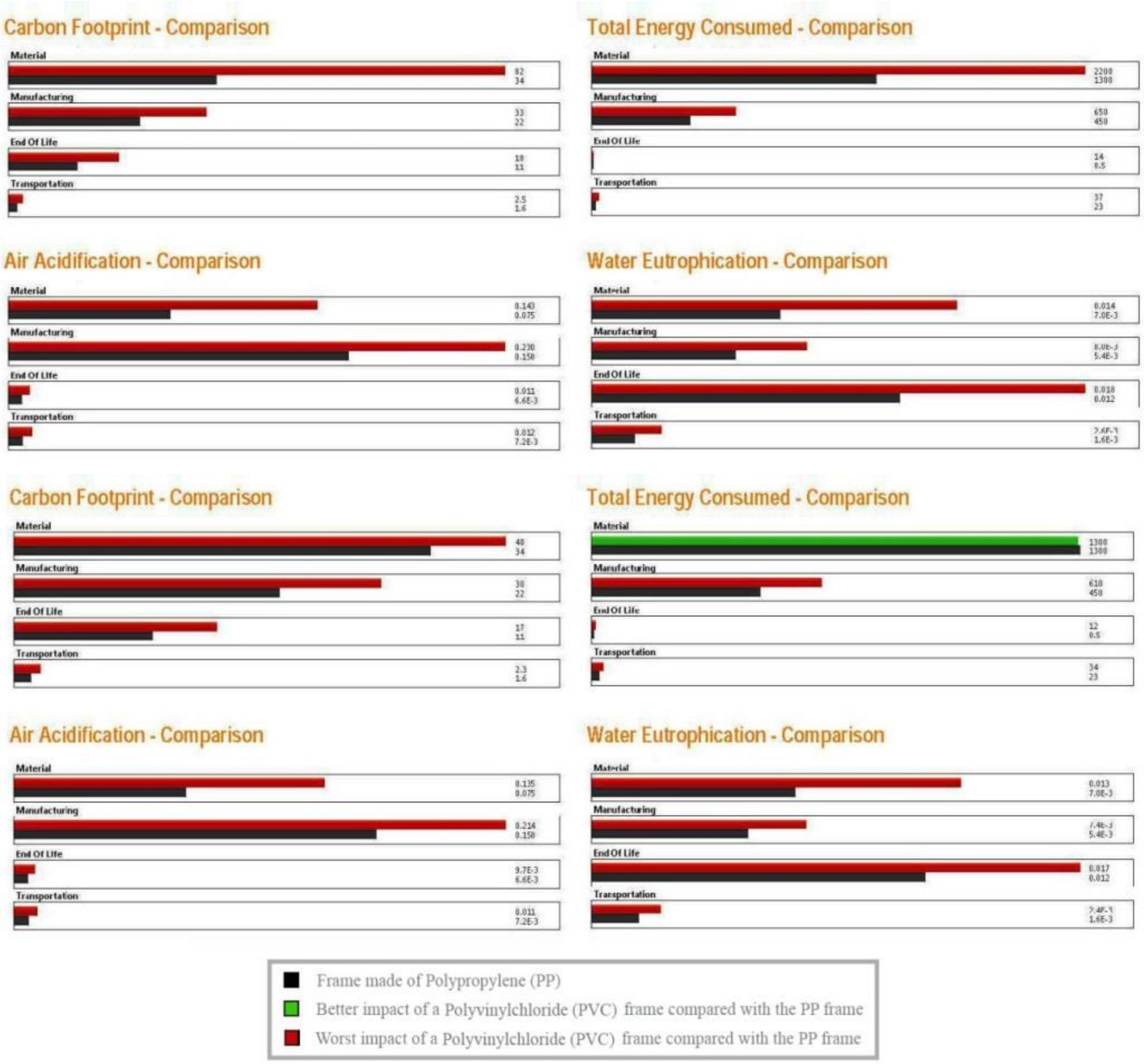


Figure 5. **Comparison of the environmental factors per lifecycle stage for the frame**

The suggested methodology is a schematic conceptual framework to introduce a systematic workflow of discrete, yet interrelated steps, in the design and analysis of a product. It is understood that not all methodologies are applicable to all design solutions, therefore, the 7-step procedure presented here addresses a design problem only partially, as there are numerous other factors that shape design ideas and facilitate product development. Recognizing the fact that the creative process cannot be easily mapped and rationalized, a conceptual framework may indeed offer a set of guidelines to designers, systematizing and structuring the sequence of design decisions. However, it is to be noted here that mental processes are not linear and they are not always driven by the exact same criteria, therefore design methodologies do aid designers to a certain extent, but there are always several other factors in play, relating to both previous experiences and knowledge as well as to overall technical expertise and discipline-related skills.

5 REFERENCES

►Benyus J. (1997). Biomimicry: Innovations Inspired by Nature William Morrow & Co

►Kyratsis P., Dimou E., Manavis A. and Bilalis N. (2015), *An inspired from nature design methodology for the fashion industry*, Applied Mechanics and Materials 760, pp 33-38

►Kyratsis P., Dimou E., Efkolidis N. and Manavis A. (2014). *Conceptual product design inspired from* *nature*, Applied Mechanics and Materials, 657, pp 1026-1030

►Brundtland G., Khalid M., Agnelli S., Al-Athel S., Chidzero B. and Fadika L. (1987). *Our common future* – The World Commission on Environment and Development Oxford University Press

►Pedersen Z. M. (2007). Biomimetic approaches to Architectural Design for increased sustainability. The SB07 NZ Sustainable Building Conference

►Adams W. (2006). The future of sustainability: Re-thinking environment and development in the twenty-first century In Report of the IUCN renowned thinkers meeting 29

►Versos C.A., and Coelho D.A. (2011). *Biologically inspired design: methods and validation*. Industrial Design-New Frontiers, pp 101-120

►Coelho D. and Versos C. (2011). *A comparative analysis of six bionic design methods*. International Journal of Design Engineering 4(2), pp 114-131

►Kyratsis P., Efkolidis N., Sirganis K. and Tsagaris A. (2012). *The environmental friendly material selection using advanced CAD systems*, Academic Journal of Manufacturing Engineering 10(3), pp 44-51.

►Efkolidis N., Garcia-Hernandez C., Kyratsis P. and Huertas-Talon J.L. (2015). *Design for Green Usability: A New User Centered Methodology for Product Development*, Applied Mechanics and Materials 809-810 (2), pp 1372-1377

►Goel A., McAdams D. and Stone R. (2014). Biologically Inspired Design Computational Methods and Tools, Springer-Verlag