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Biomimicry in Product Design through Materials Selection and Computer Aided Engineering

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Abstract. The aim of this study is to demonstrate a 7-step methodology that describes the way nature can act as a source of inspiration for the design and the development of a product. Furthermore, it suggests special computerized tools and methods for the product optimization regarding its environmental impact i.e. material selection, production methods. For validation purposes, a garden chaise lounge that imitates the form of a scorpion was developed as a result for the case study and the presentation of the current methodology.

1. Introduction
Nature is an inexhaustible source of inspiration. Since their existence, people used to observe and study nature in order to find solutions to several of their daily problems. This practice of imitating the models, systems, and elements of nature in order to solve complex human problems is known as biomimicry or biomimetics [1]. Despite the fact that biomimicry has actually a history of millions of years, namely during the whole timeline of human evolution, it was not until the recent years that it has begun to be approached in a systematic way and with a more intense interest in an attempt for more sustainable product designs.

2. Sustainability and Life Cycle Assessment
Sustainable development is the one that meets the needs of the present without compromising the ability of future generations to meet their own needs [2, 3]. Sustainability is based on three interrelated factors (economic, environmental and social), which are often found to conflict with one another. The goal of sustainable development is to achieve a complete interaction and balance between these factors in order to satisfy basic social and economic needs, while maintaining all the natural resources for future generations and improving the well-being of the environment and ecosystem on which life depends [4, 5, 6, 7].

Under the light of eliminating the negative environmental impact and comply with the three principles of sustainability, the Life-Cycle Assessment (LCA) method was used for the environmental assessment of the a chaise lounge. LCA is a method that quantitatively analyses and evaluates the environmental impact of a product throughout its entire lifecycle - from cradle to grave with all the intermediate stages. Environmental impact is associated with air pollutant emissions and consumption of resources, both of which contribute to a wide range of impacts, such as 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.

LCA is a decision making tool that calculates indicators of potential environmental impacts and provides alternative choices for potential improvements of the product under examination, identifying opportunities for pollution prevention and reductions in resource consumption. In the current research, the LCA method was implemented using the Solidworks Sustainability\textsuperscript{TM} LCA tool.

3. The Proposed Methodology
The main idea behind this project was the development of a methodology that would suggest a way of how to take advantage of a special characteristic or mechanism from a biological system and adapt it in the development of a product in order to provide a solution to a customer need. There are two distinct orientations in biomimicry as a design process \cite{8}: 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 help to the solution of the problem.

The current methodology falls in the category of solution driven methodologies and its objective is oriented on product design with special emphasis on sustainability and eco-friendliness. That was accomplished with the aid of state of the art CAD and material selection systems. The proposed methodological framework comprises 7 steps as presented in the figure 1.

![Flowchart of the proposed methodology](image)

**Figure 1.** The 7 steps of the proposed methodology
• **Research conduction:** the initial step of this project was to identify a biological system with a special feature or shape that would be the inspiration for the product development. In this case, the scorpion was selected.

• **System analysis:** the next step was to understand and analyze the morphology of the scorpion in terms of form, shape, structure and function. Scorpions have eight legs with their most recognizable characteristics being the pair of grasping pedipalps and the narrow, segmented tail, carried in a forward curve over the back, ending with a venomous stinger [9]. Through the process of abstraction and simplification a series of rough sketches were made in order to serve as the guideline in an attempt to translate its features into geometrical principles and identify any of its characteristics that could be accommodated into a daily product.

• **Problem definition:** focusing on the shape of the tail, the idea was born that it could be exploited in solving the problem of providing adequate shadow while lying under the hot sun. The concept that came up was to design a chaise lounge that would take advantage of the curved shape of the scorpion’s tail by adapting an umbrella at the tip of its backrest, where the stinger is supposed to be. In addition to the first idea, another one came up to make an adaptable slot at the tip of the backrest that could make it possible to adapt not only just an umbrella but also a mosquito net in order to provide further protection from the mosquitos’ attack or a source of light for someone who enjoys reading, while relaxing in the evening. In addition, a series of design requirements were considered (i.e. outdoor use, lightweight, modular system, minimal design, appealing shape).

• **Design deployment:** For the development of the design the following decisions were taken into account: user population (includes everyone except young children), product size (95% of the potential customers). Based on these design parameters together with the shape of the scorpion, the scaffold of the chaise lounge’s frame was developed.

• **Material analysis:** engineering materials are classified into six broad families: metals, polymers, elastomers, ceramics, glasses, and hybrids. The members of a family have certain features in common (e.g. similar properties, processing routes, etc.) and often similar applications. Furthermore, each material has particular attributes (density, strength, cost, etc.). A design demands a certain profile of these (e.g. high strength, low density, modest cost, etc.). Hence, the aim is not depicting a material but a certain profile of properties. Mechanically speaking, the frame of the chaise lounge is considered a panel loaded in bending, while the leg is considered a beam loaded in bending. Hence, both of them must be strong and stiff enough to carry compressive loads and bending moments without failure, while at the same time being as light as possible.

The translation of the design requirements of the two components is summarized in Table 1. In order to select the materials, that not only meet the design requirements previously described, but those that also maximize performance, two material property charts were examined with the use of the CES EduPack™ piece of 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:

- For the frame: polypropylene–PP (index 0.00269), polyethylene terephthalate-PET (index 0.00112) and Polyvinylchloride-PVC (index 0.001).
- 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).

• **Engineering Analysis:** this step was to assure that the chosen materials meet the mechanical requirements of the design. That was accomplished using the Finite Element Method (FEM – figure 3). For the aim of this study, each component of the chaise lounge was examined separately. Thus, stress analysis was carried out for all the 3 materials 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.

Table 1. The design requirements of the chaise lounge’s components

| FUNCTION | FRAME | LEG |
|----------|-------|-----|
| OBJECTIVE | Light and stiff frame | Light and stiff beam |

| CONSTRAINTS | FRAME | LEG |
|-------------|-------|-----|
| a. Length, $L$ (specified) | a. Length, $L$ (specified) |
| b. Bending stiffness, $S$ (specified) | b. Bending stiffness, $S$ (specified) |
| c. Fracture Toughness, $K_{IC} > 4.5 \, \text{MPa} \cdot \text{m}^{1/2}$ | c. Fracture Toughness, $K_{IC} > 15 \, \text{MPa} \cdot \text{m}^{1/2}$ |
| d. Cost, $C_m < 5 \, \text{€/kg}$ | d. Cost, $C_m < 5 \, \text{€/kg}$ |
| e. Recyclable | e. Recyclable |

| FREE VARIABLES | FRAME | LEG |
|----------------|-------|-----|
| Frame thickness, $t$ | Section Area, $A$ |

Figure 2. Use of CES EduPack™ material selection tool

- **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 finally conclude and select those materials that attribute to the design the optimum characteristics based on both the aspect of their mechanical characteristics as well as their sustainability and eco-friendliness. The evaluation of the environmental impact was achieved with the use of the 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 is conducted in two steps. In the first step, the software gathers specific environmental impacts of each component of the life cycle inventory and in the second step, the impact of the four environmental indicators were 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.

The following figures 4 to 7 depict the results of the evaluation procedure of each material and manufacturing process based on the four environmental indicators for each component separately.

| Frame | Mass (kg) | Von Mises Stress Max (MPa) | URES: Resultant 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) | Von Mises Stress Max (MPa) | URES: Resultant 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                                |

Comparing the results in the charts (figures 4 to 7) and in figure 3, polypropylene (PP) is the most appropriate material for the production of the frame since it meets the mechanical requirements of the product and additionally it will lead to a frame with the lowest weight. 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 on the aspect of 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.

Figure 3. FEM implementation
Impact of the PP frame material on the environmental factors

Impact of the PET frame material on the environmental factors

Impact of the PVC frame material on the environmental factors

Figure 4. Frame’s materials impact on the environmental factors
Figure 5. Leg’s materials impact on the environmental factors
4. Conclusion

The aim of this study was to propose a methodology that can be used in product design and which combines biomimicry with sustainable development. As a result, more eco-friendly and green products are to be produced. The aim of this methodology is to provide a roadmap for a potential product designer in order to exploit nature as a source of inspiration for the design and development of a product, while at the same time, optimizing this product in terms of its environmental impact utilizing state of art computerized tools.

It should be mentioned that no matter how well-structured a methodology is, it is not a panacea to the success of a product, since there are many other factors affecting it, two of the most prominent being the creativity and the technical expertise.
Figure 7. Comparison of the environmental factors per lifecycle stage for the legs

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