Environmental Re-design of the Top San No Touch 2.0 Portable Toilet: The Contribution of the Bio-inspired Approach

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Abstract. This research is part of the scientific discipline of Design for Environmental Sustainability and Industrial Design, and deals with the topic of the relationship between bio-inspiration and ecodesign as a promising synergy for the design of industrial products.

This contribution describes the methodological process addressed to investigate, analyse and quantify the contribution offered by bio-inspiration, an approach considered to be a driver of innovation aimed at increasing the environmental sustainability of products.

In order to understand and verify the real advantages that the bio-inspired approach can offer, in terms of environmental sustainability, to the design of industrial products, a bio-inspired redesign of a sustainable product in possession of environmental quality certification was undertaken, in order to quantitatively assess the product's life-cycle environmental impacts through the standardised LCA methodology.

In order to achieve the stated objective, the research was conducted with different methodological approaches and operational tools according to the research phases, interacting with experts from different fields and scientific disciplines which allowed the acquisition of complementary technical-scientific knowledge.

Keywords: Biomimicry · Design for Sustainability · Bio-inspired redesign · Comparative LCA

1 Introduction

Within the scientific discipline of Design for Environmental Sustainability, the biomimetic approach applied to design culture is becoming increasingly popular. Biomimicry is the discipline that studies natural biological systems in order to emulate them in forms, processes and strategies useful for finding more sustainable solutions to human design and technological problems [1].

The increased understanding of nature's solutions is also due to the recent development of new scientific knowledge and technological tools, in particular nanoscience and nanotechnology. The latter make it possible to analyse, describe and reproduce hitherto unpublished and unexplored aspects and processes of nature at the nanometric scale [2].

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Although its epistemology still seems to be under construction, the discipline offers a set of tools and guidelines to support the design process in order to develop high-performance materials and artefacts [3].

Biomimicry, which is based on the emulation of principles found in nature, starts from the "assumption that if one imitates nature, one automatically returns to an inherently eco-sustainable state, since nature by definition operates in a sustainable manner" [4]. This assumption is often justified by the evolutionary optimisation process lasting millions of years, making bio-inspired solutions innovative, ecologically viable, resilient and low-risk.

While these premises are conceptually valid, biomimetic products do not always guarantee optimal qualities, and this may be due to multiple factors, such as scalarity: characteristics observed in nature cannot always be directly transferred and scaled to the project, thus risking the application of inefficient solutions [5].

Although there are hypotheses of tools aimed at quantifying the sustainable potential of biomimetic products [6], the literature review shows that such environmental benefits have rarely been quantified [7].

This last open question represents the focus that this research intends to investigate, and thus aims to verify the real environmental benefits that the biomimetic approach can offer to the design of industrial products.

In line with the Design for Environmental Sustainability design criteria that were realised by re-designing existing objects, the research undertook a redesign of a certified sustainable product to verify the environmental benefits that the biomimetic approach can offer over and above the established eco-design guidelines and strategies, in terms of sustainability.

The aim of the research is therefore to quantitatively explicate, through a Life Cycle Assessment and comparison between the starting product and its bio-inspired re-design, the environmental benefits obtained from the biomimetic approach.

The methodological process that follows sees the articulation of two macro-phases that led the research in the achievement of the main objective: the first one focuses on the research and selection of the case study, while the second macro-phase concentrates on the bio-inspired design development of the product followed by the comparative environmental analysis between the case study and its biomimetic re-design. It is a research process conducted with different methodological approaches and operational tools depending on the phases, interacting with experts from disciplines other than the design field and acquiring complementary technical-scientific knowledge useful for research development.

2 Research, Selection, Analysis of Case Study for Biomimetic Design Experimentation

Of fundamental importance is the first selection parameter, which involves the identification of products with environmental quality certification. The research focused on the study and analysis of voluntary eco-labels and environmental labels included in Integrated Product Policy - IPP [8]. It was therefore appropriate to examine the voluntary labelling systems defined by the UNI EN ISO 14020 standards, directing research towards Type III certifications, i.e. environmental declarations that contain a quantification of the environmental impacts associated with the product's life cycle calculated through the Life Cycle Assessment system.

The numerous products of interest for design with environmental certification and declaration led the research to define selection parameters in order to identify the case study for the bio-inspired design experimentation process. These parameters exclude

– product categories whose performance is given by the exclusive use of material (such as paper, textile, ceramic products);
– energy-consuming products, as the life-cycle environmental impact manifests itself mainly in the use phase;
– products that do not belong to Made in Italy and design-oriented companies, as the intention is to relate to and collaborate with production realities with a high interest in design and the issue of environmental sustainability.

The application of the selection criteria and the subsequent evaluation of the quality and quantity of the available data resulted in the selection of the Top San No Touch 2.0 portable toilet from Sebach s.p.a., Italy's leading product service rental company (Fig. 1).

According to the European standard UNI EN 16194 [9], a portable toilet is an independent portable unit intended for use by a single person, equipped with a waste tank that is not connected to the sewage system. It is a product with similar functions to the sanitary facilities located in housing developments and connected to the sewage system. Although configured in an essential manner, the portable toilet is a rather complex product and is mostly made of high-density polyethylene using injection moulding technology.

Following agreed relationships with the company, the technical analyses necessary for understanding the product were elaborated. The analysis of the environmental impacts supplementary to the EPD, through the standardised Life Cycle Assessment methodology, made it possible to identify options for environmental improvement of the portable toilet to be considered in the bio-inspired design development.

The first analysis relates to the architecture and functionality of the product and its role along the phases of the rental service. The mobile bath is characterised by a parallelepiped shape with a vertical major axis. The roof at the top of the bath is slightly rounded to allow rainwater to run down the sides, while the platform is equipped with side skids to allow the product to be lifted by forklift forks. The side walls are fixed to the roof and the platform to ensure structural rigidity, and on one of the four sides there is a door hinged to the boarding which, opening outwards, allows the entrance of the users of the portable toilet who will be able to use the toilet unit located inside the cabin. Through the study of current regulations and reverse engineering on the physical product, the architecture of the Top San No Touch 2.0, an abacus of components and summary sheets of the performance qualities of the portable toilet were drawn up.

At the same time, the result of the field research activities for the collection of photographic and audiovisual material and interviews with Sebach dealers were drawn up summarising the phases of the rental service and the product performance qualities in relation to the individual service phases. At the end of the various analyses performed, it was possible to create a synthesis of the formal, functional and performance aspects

Fig. 1. The Top San No Touch 2.0 portable toilet, Sebach S.p.a.

of the product integrated with the regulatory requirements and characteristics of the company's production reality.

The second technical analysis focused on the calculation of product life cycle environmental impacts in order to verify and supplement the data in the Environmental Product Declaration. Only summary tables of the environmental impact values are given in the document. It was therefore necessary to rework the LCA calculation, according to the standardised Life Cycle Assessment procedures and using the Eco-It PRé Consultants software, in order to acquire the Co2 equivalent(measure that expresses the impact on global warming of a certain amount of greenhouse gases compared to the same amount of carbon dioxide) values of each component of the portable toilet in relation to the product life cycle phases. From the interpretation of the quantitative data that emerged from the calculation, it can be stated that the greatest environmental impacts are found in the production of the macro-components that make up the cabin, i.e. the roof, side walls, skirting, door and platform.

By systematising the information from the technical analyses, it was possible to identify two eco-design objectives to be pursued in the biomimetic re-design process. The first objective concerns the elimination of non-reversible joints, pertaining to the eco-design strategy of "facilitating product assembly and disassembly" [10]. The parts of the portable toilet are connected by the use of rivets, a type of connection that does not allow them to be reused if a component is replaced. A total of 73 rivets are currently used to connect the parts of the central body of the portable toilet along the vertical edges, and the same to the footboard and roof.

The second objective relates to the eco-design strategy of "minimising the consumption of environmental resource" [10] by taking design action to reduce the amount of material used in the production of the components. The central elements of the portable toilet, i.e. the side wall - 3 of which are needed to form a portable unit - and the barrel-holder assembly, are characterised by a significant vertical development of approximately 2 m. Injection-moulded in HDPE, the central elements are manufactured with a constant thickness of 4 mm to guarantee rigidity and structural strength.

The side wall component, i.e. the component of the central part of the portable toilet covering three sides of the cabin, is taken into consideration for the start of the experimental design phase. This component is a priority for the achievement of the two redesign objectives, both in terms of its dimensional and functional aspects and as a nodal element for the configuration of the new reversible connection system.

3 Bio-inspired Product Re-design and Comparative Environmental Analysis

The biomimetic design experimentation of the wall component involved the application of the Topdown approach methodology. Starting from previously outlined specific objectives, we proceed to research and identify the biological model that offers corresponding solutions, and then abstract the natural functions and principles into design strategies in order to apply them to the new design.

The exploratory research process of biological models was characterised by research activities and information gathering through the consultation of specific databases, such as asknature.org of the Biomimicry Institute, and the dedicated bibliography. The exchange of information between the discipline of design and the discipline of biology was made possible through interactions with experts from the natural world: through analogical thinking, biological strategies and principles were identified that met the objectives of eco-design for re-design.

For the development of a reversible system of connections, the "temporary attachment" functions were explored. i.e. the connections that nature adopts or makes to survive or evolve. Living systems sometimes have to stay in one place, climb or move temporarily, which includes the ability to release the cling if necessary. Despite being temporary, connections must resist physical forces until they have served their purpose. Therefore, living systems have adapted attachment mechanisms optimised for the amount of time or number of times they must be used. Examples include insects that attach their eggs to a leaf until they hatch, and insects whose wings temporarily attach during flight but separate after landing. Connections in nature can be manifold, such as the caterpillar of the Gaia Oto butterfly, or the hooks of the burdock that inspired De Mestral in realising the recognised reversible Velcro connection. The re-design of the product connections therefore envisages the abstraction and application of the reversible coupling principle, without the use of additional material, but by deriving the function directly in the relevant parts of the side wall.

In order to achieve the second objective, i.e. to slim down the thickness of the wall component in order to use less material, the abstraction phase takes into account the strategy of structural resistance per shape present in many biological models. For example, the scallop has a very thin shell, but thanks to its surface deformation it manages to provide just as much structural resistance. Another useful function in achieving the second objective is the principle of the hierarchy of elements, found for example in the dense network of reinforcing ribs below the surface of the Victoria Amazon leaf, which suggests the rational distribution of material.

The process of transposing the identified natural logics to the design development was conducted by applying the biological principles to the technical functionality of the side wall of the portable toilet. Design constraints related to the material and production technology, i.e. injection-moulded HDPE, were considered, as well as the formal-functional constraints of the component and the quality requirements dictated by current regulations. In this phase, multi-disciplinarity was a fundamental characteristic for the development of the biomimetic re-design process, while the tools adopted included graphic representation techniques for the conception of the new design, software for parametric 3D modelling (Autodesk Fusion 360) in order to have greater control over the modifications to be made, specialist software (Altaire Inspire) for verification analyses of the functional performance that the product must possess and guarantee, and the physical models for study and rapid prototyping using 3D printers for precise verification of the formal and functional aspects of the new design.

The re-design of the bioinspired reversible connection system focused on the assembly of the central body of the portable toilet, i.e. the three sides occupied by the side walls and the fourth side defined by the barrel-holder assembly. The surfaces of interest for the design intervention are therefore the vertical angles of the component. Following the current assembly phases of the portable toilet, once the wall has been positioned at the bottom, it is possible to continue with the positioning of a further wall on one of the adjacent sides. The new connection system between the vertical elements involves hinges machined directly from the mould of the component in order to obtain movable parts that house the vertically developed quick-release couplings inside them (Fig. 2a). These hinges are alternated with fixed parts: in this way, the movable parts of the first wall can be attached to the fixed parts of the corresponding angle and vice versa. To complete the coverage of the central part of the mobile bath, the imbotte component must also be fitted with the new reversible connection system from the corner pieces. By configuring a continuous module in this way, the central elements of the portable bathroom can be assembled manually. Disassembly of the snap-fits is made possible by using a specially designed accessory which, by inserting itself into the slots at each snap-fit, can lever the pin out of the snap connection.

The area of interest of the side wall for the bio-inspired design development to minimise material use was focused on the central part of the component. In order to

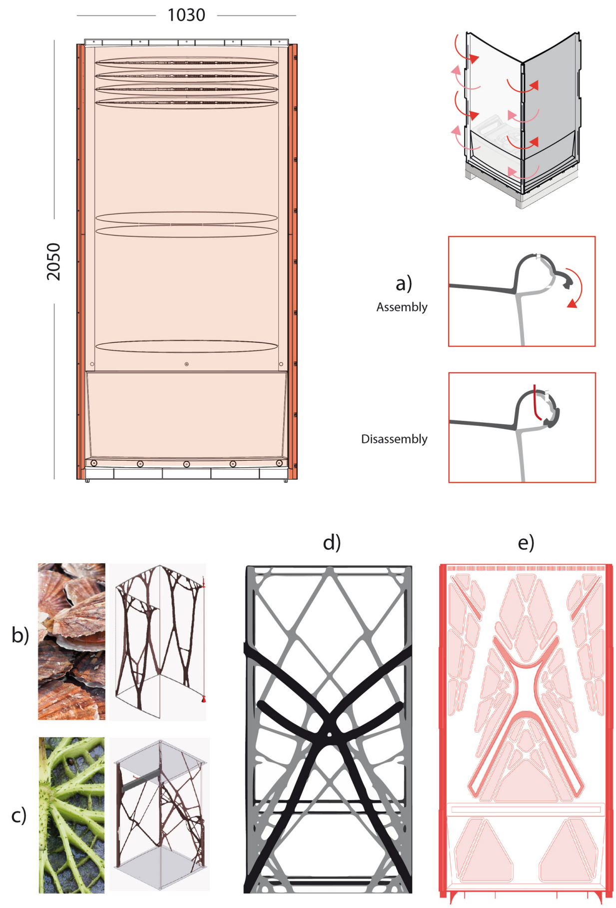

Fig. 2. Biomimetic design development of the side wall of the portable toilet.

understand how much less material can be used, it was necessary to identify the areas of the wall subjected to higher loads and/or stresses from, for example, product handling. This operation was made possible thanks to the topological optimisation of the component, i.e. the study, carried out with the Altaire Inspire software, capable of redefining the shape of the model, allowing the part to be lightened by subtracting unnecessary material in order to maintain the structural properties. In order to plan the analysis, it was necessary to involve researchers from the Unicam Structural Engineering area to define the characteristics of the 3D model, the constraints and the loads to be subjected to calculation, thus identifying two types of topological optimisation analysis. The first analysis, relating to the application of the principles of structural resistance by shape, aims to understand how the cabin structure reacts to loads from above (Fig. 2b). The second analysis, relating to the hierarchy and rational distribution of material according to forces (Fig. 2c), was planned to understand the behaviour of the structure when subjected to horizontal loads (force that could be generated by vandalism, for example). The topological optimisation operation follows the logic of emptying, and since the component cannot have any holes or openings, it was necessary to identify the main lines that constitute the base line for the bioinspired redesign of the wall (Fig. 2d). We then began the process of formalising the component through its biomimetic principles, aiming to reduce the constant 4mm thickness of the current wall. Starting from a basic design modelled in a parametric environment - Autodesk Fusion 360 - and the continuous structural evaluation, by means of OptiStruct analysis of the Altaire Inspire software, it was possible to define the design from time to time until obtaining a model that guaranteed structural resistance with the same performance as the current one. The result is a side wall with a constant thickness of 2.6 mm characterised by surface movement: there is a base layer from which certain areas of the wall protrude towards the outside of the cabin (in light red) and areas that retract towards the inside of the cabin (in dark red, Fig. 2e). Thanks to the thickness thinning operation for the construction of the side wall, the weight and use of material has been considerably reduced: the current component is characterised by a constant thickness of about 4 mm and uses 9.7 kg of high-density polyethylene; the bio-inspired side wall, on the other hand, is characterised by a constant thickness of about 2.6 mm, guaranteeing the same structural strength performance as the original element, with 6.537 kg of HDPE used.

At the end of the bio-inspired re-design, it was possible to start the comparative environmental analysis phase with the original side wall. Although still in progress, it is possible to return the first results of the comparison between the two components for the production of the side wall alone. Following the standardised Life Cycle Assessment methodology, data was entered into the Eco-It PRé Consultants software regarding the number of components - of which it should be noted that 3 walls are needed to make a portable toilet -, the quantity of material and the injection moulding processing technology. The software works with Eco-indicators, choosing to return the following results according to the IPCC 2007 assessment method expressing Co2 equivalent. The LCA calculation shows that:

– the production of 3 current side walls generates a total of 95 kg Co2-eq,
– the production of three bio-inspired side walls generates a total of 64 kg Co2-eq.

This results in a reduction in environmental impacts of around 30% compared to the original. A substantial reduction that generates advantages not only in terms of the quantity of material to be used, which translates into a reduction of environmental impacts, but also in terms of costs, thus drawing economic benefits. In addition, the new reversible connection system allowed the impacts generated by the production of 73 rivets to be eliminated from the LCA calculation, amounting to −5% Co2-eq. Again, the benefits obtained have positive repercussions in other phases of the product life cycle, such as the reduction of time to be spent in the assembly and reconfiguration phases of the portable bath by Sebach operators.

4 Conclusions

The research process just described aims to answer an important question that the scientific literature has implicitly and explicitly begun to raise, namely whether indeed the biomimetic approach can automatically transfer more sustainable solutions into industrial product design. The question in this research has been formulated more specifically, namely how many more environmental benefits the biomimetic approach offers than the established eco-design guidelines and strategies. The aim was to undertake a bio-inspired redesign of products already conceived and manufactured according to eco-design strategies, in order to quantitatively assess the contribution of Biomimicry. The design development had to meet the necessary requirements in order to achieve a truthful quantitative assessment of the environmental impacts of the re-designed components: the high degree of manufacturing feasibility consistent with the reference business reality of the case study, the technical and regulatory requirements of the product, as well as a design consistency of the formal, functional and performance aspects to be maintained in the new product.

The process of bio-inspired re-design of the prioritised parts of the product and the subsequent environmental assessment, although still at the in-depth stage, enabled the comparative analysis between the result of the conducted design development and the original TopSan NoTouch 2.0 portable toilet product. Initial results of the comparative environmental analysis show that Biomimicry can concretely contribute to the generation of more sustainable products, and that the relationship between the Biomimicry approach and eco-design appears to be a promising synergy for the development of a new generation of products with a low environmental impact. Biomimicry, if practised thoughtfully and consciously, and with clear performance objectives in environmental terms, can be a powerful design tool that supports innovation [11].

A further achievement concerns the methodological aspect of the process addressed in this research. Specific methodologies and tools had to be adopted for each phase of the process. Consider (i) the phases of environmental assessment using LCA methodology and tools, (ii) the phases characterising the biomimetic approach to the project by interacting with biology experts and consulting specific databases, (iii) the use of specialised operational tools for bio-inspired project development to which the interpretation of results required continuous comparisons with researchers from the structural engineering discipline. The interdisciplinary aspect is therefore of fundamental importance for the development of research projects of this nature.

Finally, the acquisition of specific knowledge throughout the research process leads to reflections on the role of the designer, which is different from the past especially in complex research topics. A role in which the integration of knowledge of different approaches, methodologies and specialised operational tools is of fundamental importance to enable designers to hold a central position in conducting research processes of this nature.

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