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Structural optimization strategies to design green products

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ABSTRACT

This paper addresses the need for a structured approach to environmental assessment and improvement. We propose a computer-aided methodology, named Eco-OptiCAD, based on the integration of Structural Optimization and Life Cycle Assessment (LCA) tools. Eco-OptiCAD supports the designer during product development, highlighting when and where the core of the environmental impact lies. Furthermore, it provides effective tools to address such impacts, improving the original product, while ensuring structural and functional requirements. It foresees the synergic use of (1) virtual prototyping tools, such as 3D CAD, Finite Element Analysis (FEA) and Structural optimization, (2) function modeling methodology and (3) Life Cycle Assessment (LCA) tools. The kernel of the methodology is constituted by a set of optimization strategies and a module, named Life Cycle Mapping (LCM). In particular, we have conceived ten optimization strategies converting environmental objectives and constraints into structural and geometrical parameters. They enable the designer to generate alternative green scenarios according to the triad shape–material–production. The LCM tool has been specifically developed to easily trace the growth of environmental impacts throughout the product's life cycle and allow the user to focus his effort on the most relevant aspects. Thanks to the integration of the structural optimizer with an LCA map, the designer becomes aware of the consequences that each change in the geometry, the material or the manufacturing process will produce on the environmental impact of the product throughout its life cycle. With a complete view of the product life cycle, the designer can improve a single phase, while retaining a global perspective; thus avoiding the possibility of gaining a local green improvement at the cost of a global increase in environmental impacts.

An exemplary case study is presented to detail each step of the design methodology and shows its potential. Eco-OptiCAD represents a first step toward a fully integrated system for eco-design assessment and improvement, with the potential of working side by side with common design tools, in providing a constant environmental feedback.

1. Introduction

Nowadays, after many years of inconsiderate exploitation of natural resources, the human interaction with the environment is under the spotlight of researchers. Forecasts about earth health are not encouraging and environmental issues are going to be one of the main concerns of our time.

From an engineering perspective, eco-design of products and production processes is the leverage to reverse the tendency and gather full eco-compatibility of industrial activity. The challenge eco-design has to face is to perform functions to fulfill a need or to provide a benefit to the customer keeping into account products interactions with the environment along the entire life cycle. It is imperative that designers consider environmental factors in addition to technological and market-derived requirements, from the early stage of conceptual design and through all product development. In fact, a debate is ongoing about if and how environmental costs must be counted in the global cost of the product [1].

Eco-design, or green-design, consists of a set of coordinated activities aimed at developing products and processes with less environmental impact. Four levels of eco-design can be identified [2]:

Level 1 – Product improvement: a progressive and incremental improvement of the product, i.e., a re-styling. For example, one can decrease the materials consumption or replace a type of fastener with another.

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Level 2 – Product redesign: a new product is redesigned on the basis of an existing one.
Level 3 – New product concept: it is an innovation rupture; technical functions, which fulfill product functionality, are changed.
Level 4 – New production system: it occurs when innovation in the productive system is required.

In this paper we present an innovative framework to support Levels 1 and 2. Our aim is to assist the designer during the embodiment phase, meant as "determining the preliminary general arrangement and shapes of all materials and components" [3]. This is done by introducing a set of computer-aided tools in a structured process, which permits to simultaneously manage three key features of the product (shape, material and production method) and to obtain the minimum environmental impact. This implies a radical change in the concept of eco design, from a systematic variation of possible solutions, as suggested by all eco-improvement methods, to a critical and formal selection of the optimal solution. To achieve this goal, we propose a computer-aided approach based on the integration of Structural Optimization and Life Cycle Assessment (LCA) tools. In particular, we have conceived a set of structural optimization strategies, which enable the designer to generate a series of product variations with a lower environmental impact, estimated adopting a full LCA approach. Thanks to the integration of the structural optimizer with an LCA map, the designer becomes aware of the consequences that each change in the geometry, the material or the manufacturing process will produce on the environmental impact of the product along its life cycle, allowing for better results than those granted by whatever "Design for X" approach. The proposed design approach foresees the synergic use of (1) virtual prototyping tools, such as 3D CAD, Finite Element Analysis (FEA) and Structural optimization, (2) function modeling methodology and (3) Life Cycle Assessment (LCA) tools.

In this paper, we first present the state of art in the field; then, the proposed methodology is described in detail. An exemplary case study related to a moped rim is also presented to demonstrate the potential of the methodology. The paper is completed by a discussion of the results achieved so far.

2. Previous works

During the last decades several tools have been specifically developed to support eco-design [4]. The purpose can be different, as described by Byggeth et al. in [5], and few of them support every life cycle phase.

Knight [4] grouped them into 3 categories:

1. *Guidelines*: They provide broad support with little detail, but they are applicable either across the whole product life cycle or a significant area (e.g., design for recycling, design for disassembly, and design for lifetime optimization) [6,7].
2. *Checklists*: They provide in-depth, but narrow, application at selected stages of the product development process or life cycle [8,9].
3. *Analytical tools*: They provide detailed and/or systematic analysis at specific stages either of the product development process or life cycle (e.g., eco-indicators, environmental effect analysis, environmental impact assessment, life cycle assessment, material, energy and toxicity ('MET') matrix, and life cycle cost analysis) [10,11].

These tools are not systematically used in the product development process [12] and very few of them prove to be a working tool rather than just a practical common sense indication. While suggesting how to modify a product to improve its environmental performance, these methods fail to provide a direct link with LCA assessment tools. Therefore, it becomes difficult to assess whether a design choice represents an improvement on the environmental impact of the product, unless one applies a new LCA.

Other methods, not properly classified as eco-design tools, are those known as methods of "Form Design". They come from the design school and they pursue exactly the same goals of the previous ones. They focus on the principles of minimum space requirement, minimum weight and minimum losses [13]. Form Design is characterized by the simultaneous application of physical and economic laws, and leads to the determination of shape and size of components and to an appropriate choice of material, production methods, etc.

In the last decade there have been many attempts to integrate Eco-design within CAD environments, in order to generate greener products by changing materials [14,15], manufacturing bill of materials [16], manufacturing process configurations [17,18], product service systems [19] or generating a new shape [20–23]. However, we can find few CAD applications for eco-design that have been really implemented. Even so, they are based on conversion tables of materials and processes (e.g., Ecoinvent Database (http://www.ecoinvent.org/database/), PE Database (http://www.pe-international.com/services-solutions/product-sustainability/data-on-demand-databases/), Industry Data v.2 Database (http://www.plasticseurope.org/), Input-Output databases for Life Cycle Assessment (http://www.lca-net.com/products/io-databases/) associated with the different parts or assemblies of the product, in terms of key environmental indicators [24–31]. Eco-Indicator 99 [32] is often used to aggregate all impacts into a single numeric parameter.

The key aspect of CAD tools is the way product information is structured; in fact:

- Product (assembly) is already organized by separated parts allowing an arrangement of results by components.
- Information about material, transport and manufacture process, cost, etc. can be easily associated to each part, thus including other life cycle phases traditionally neglected in a standard design approach.
- Intuitive design and user-friendly interface.
- Automatic calculation of mass and volume of all product components.
- Easily implementable material and item statistics.
- Easy back tracing of environmental hotspots through the product structure.

Fig. 1 portrays the evolution of computer-aided tools for eco-design during the last decade.

Roche's work was, probably, the first attempt to undertake environmental Life Cycle Assessment during product development [26]. It describes a new framework for Design for Environment (DfE) and a development tool integrated in a CAD environment (ProEngineer).

EcologiCAD, developed in 2004 by Leibrecht [24,25], customized ProEngineer 3D-CAD structures to create environmental assessment based on existing product data. To calculate the results, the impact analysis uses a simplified approach linking components information (mass, volume, life time and material) to an environmental database containing 36 different types of indicators. Results are finally normalized to a functional unit, which accounts for the life duration of each component, and are then plotted by graphs and statistics. EcologiCAD does not offer guidelines or a list of materials.