An ECO-DESIGN Approach Based on Structural Optimization in a CAD Framework

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ABSTRACT

This paper proposes a design approach to support the designer during the environmentally sustainable redesign of any product that can be modeled in CAD environment. It is a systematic computer-aided design procedure based on the integration of (1) virtual prototyping tools (e.g., 3D CAD, FEA, structural optimization), (2) function modeling techniques, and (3) Life Cycle Assessment-LCA tools. The core of the approach is the configuration of structural optimization strategies specifically conceived to obtain lighter and more compact products, and therefore, more eco-sustainable. The objective of the proposed methodology is to support the designer in choosing the best triad shape-material-production in order to determine the minimum environmental impact and ensure the structural and functional requirements of the product. A case study is described to show the potential of the proposed methodology as well as a discussion of the results.

Keywords: eco design, CAD, structural optimization, LCA.

1. INTRODUCTION

During previous decades, engineers were only concerned about designing products that met given requirements and paying little attention to the future availability of natural resources. Current design trend is changing; in fact, the product has to fulfill either functional performances or market needs and, at the same time, to ensure the maximum added value with minimal material and/or energy wastage.

To achieve this goal, many eco-design tools (guidelines, checklists and analytical tools) have been conceived to identify where it is more useful to intervene, and how to improve current products and processes [1–3]. While suggesting how to modify a product to improve its environmental performances, these methods fail to provide a direct link with a Life Cycle Assessment-LCA system. Therefore, it is difficult to assess whether a certain design choice represents a right direction of intervention and results in a significant influence on the overall environmental impact of the product unless one makes a new LCA.

From an engineering perspective, eco-design of products and production processes is the leverage to gather full eco-compatibility of industrial activity.

We can observe that most of eco-design tools are mainly targeted to eco assessment. In 2006, a survey of 65 LCA practitioners [4] reported that 58% used GaBi (PE International), 31% SimaPro (PRé), 11% TEAM (Ecobilan). Other cited tools are: BEES (NIST), Umberto (ifu Hamburg), ECO-IT (PRé), excel-based spreadsheets, math packages (e.g., MATLAB and Mathematica), and Everdee. However, eco-improvement tools are not connected/linked to the assessment step.

CAD system can be considered the best tool to link assessment and improvement since the product (assembly) is already organized in parts allowing an arrangement of results by components. In fact, the tree-structure of the product represents a good starting point for Life Cycle Inventory (LCI).

There have been some attempts to integrate CAD and LCA linking each component to the database for the calculation of the environmental impact. The 3D CAD system calculates mass and volume of each part that can be used as input to determine the impacts for the packaging and transport phase. There are also some examples of calculating the impact of energy consumption during product manufacturing simply considering the mass/material of the component. Moreover, the CAD-FEM integration permits, in theory, the integration with CAM tools to evaluate the energy necessary to manufacture the component by calculating the machining time.

We usually proceed by trial and error. One models the part; then, associating different materials, one tries to understand if the selected indicators can increase or not.

However, data associated with each part of the product are not related to all phases of the product life cycle. In fact, end of life and use phases are not considered, while for the manufacturing phase the output is the result of a very rough analysis, with the consequent loss of reliability. In any case, we are never able to perform a real LCA to identify the critical elements and take the appropriate decisions.

The user, working component by component, does not have a global view of the product impact limiting in such a way the effectiveness of his/her decisions. It is not easy to identify from the structured flow of information the part that pollutes more than others and, in any case, we cannot associate its contribution with all phases of its real life cycle. Therefore, it is quite impossible to apply eco-improvement suggestions since they operate at the system level and never at the component level.

The work described in this paper aims at overcoming above-mentioned limits and making the designers more aware of the impact of their design choices on all phases of the product life cycle. We propose an eco-sustainable computer aided design procedure based on the integration of (1) virtual prototyping tools (e.g., 3D CAD, FEA, structural optimization), (2) function modeling methodology, and (3) LCA tools. The objective of the proposed methodology, named Eco-OptiCAD, is to support the designer in choosing the best triad shape-material-production in order to determine the minimum environmental impact and ensure the structural and functional requirements of the product.

In this paper, we first analyze current solutions based on CAD-LCA integration, especially that one realized by Solidworks Sustainability; then, we describe the proposed design procedure, which permits to create eco scenarios based on different triads shape/material/manufacturing process and to evaluate all the product life-cycle. Finally, the application of the proposed methodology to the case study of a connecting rod is presented as well as a discussion of the results reached so far.

2. ANALYSIS OF EXISTING SOLUTIONS

The aim of CAD-based tools for eco-design is to measure variations on environmental impact indexes not at the end but during the design activity [5], monitoring any change onto the product and at the same time tracing the best promising direction of intervention.

There have been attempts to generate systematic product variations in CAD environment [6–13]. CAD-based functions are used to ensure that the variations satisfy product functional requirements. However, only few CAD applications for eco-design (really implemented) have been identified in literature [12,13]. An example is EcologiCAD, developed in 2004 by Leibrecht [12]. In this case, once identified the component to work with and applied the proposed guideline, there is no guarantee of success. Anyway, none of them have a full LCA or abridged LCA (aLCA) approach; rather, they are based on conversion tables of materials and processes associated with the different parts or assemblies of the product, in terms of key environmental indicators, such as the Eco-Indicator 99 [14].

The first commercial module for eco-design appeared in 2009 as a free plug-in for SolidWorks 2009, called Solidworks Sustainability. This module, still presents on the market, incorporates pre-production modeling of environmental impacts into the product development process and uses secondary LCA data to develop a quick assessment, called "screening LCA" [15]. Since it doesn't use the company primary data, it shouldn't replace comprehensive LCA software and should be used as an environmental impact dashboard, giving immediate feedback on the impact of some design decisions. Impacts are calculated by PE International's LCA database, but for a complete LCA it requires a general process model realized using the GaBi LCA software, that is not embedded.

Solidworks Sustainability integrates libraries for transports, materials and manufacturing processes. Transports are listed in decreasing order of environmental impact and they are air, truck, rail and ship transport. Besides distance and type, another factor is the quality of the fuel used, regionally dependent. For example, fuel in Asia often has a higher sulfur content raising the acidification potential of the transport leg. The use phase is integrated and the user has to fill the energy consumption of the product during the all lifetime according to functional unit selected. No aided tools or libraries are provided.

Regarding material selection, the system provides the "Find Similar" tool (Fig. 1) to find a material that satisfies all criteria: it must function as intended, it must provide the right aesthetic, ergonomic, and other form considerations, its cost must be in the range of the product's cost of goods and finally material environmental impacts should be minimized.

Finally, a new feature has been added for integrating the manufacturing processes. Impact is calculated multiplying the mass of each component/assembly by the index of the relative process (taken from the PE International LCA list). Unfortunately only few inputs are allowed to customize the process; the approach is affected by low reliability and doesn't allow shape/material/manufacturing process to be evaluated at the same time. The impact can be visualized in different forms: a ranking of the components for each indicator or comparing each component by many indicators (Fig. 2).

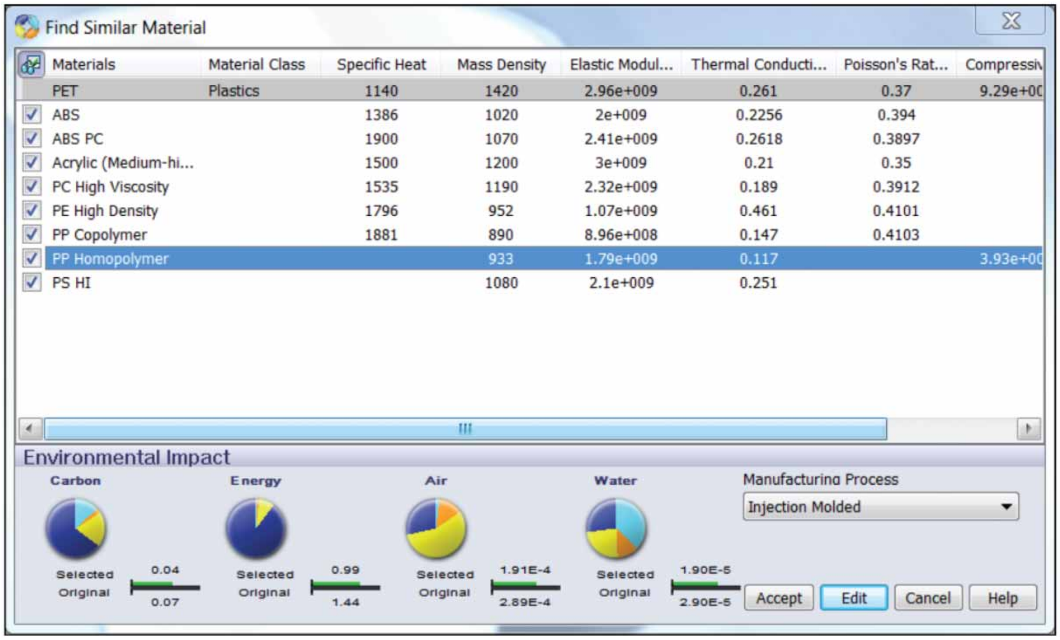


Fig. 1: “Find Similar” material selection tool (Courtesy Solidworks Sustainability).

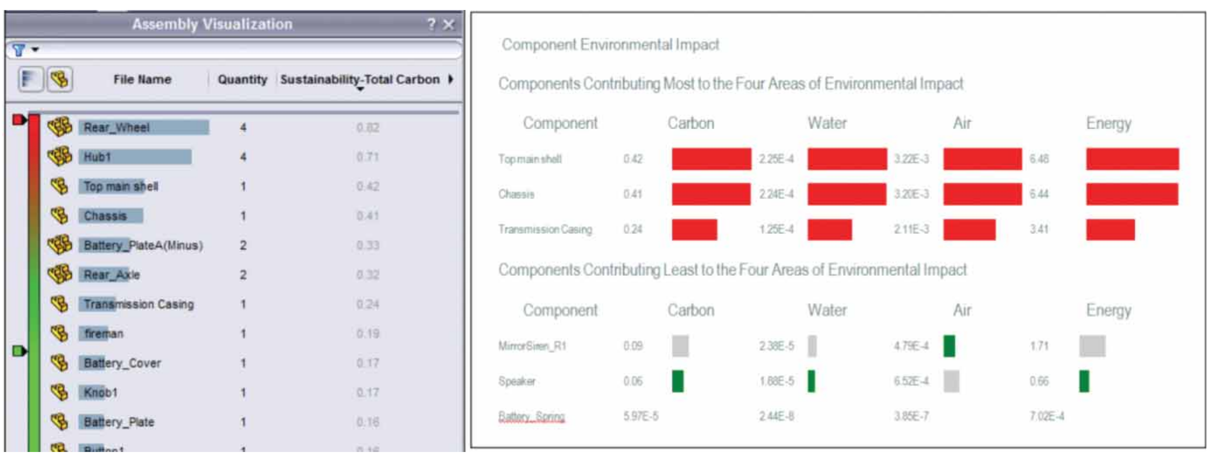


Fig. 2: Environmental ranking output (Courtesy Solidworks Sustainability).

Another issue mentioned before concerns the integration with CAE tools. In fact, one of the main strategies for green product is to design lightweight products. When less material is required at the manufacturing phase, less material has to be extracted, processed and shipped in the previous phase. A lightweight product means also less energy in the use phase. A critical consideration for load-bearing materials that are being light weighted is to ensure that the product still complies functional requirements. Solidworks module suggests using simulation tools to optimize strength and reduce impact, but no strategies are proposed.

3. ECO-OPTICAD APPROACH

Eco-OptiCAD supports the designer in choosing the best triad shape-material-production to identify the minimum environmental impact and meet simultaneously structural and functional requirements of the product. It integrates:

1. *Virtual prototyping tools*, precisely:
   - A 3D CAD system to model the product and its variants. It is also used to automatically calculate the values of mass, volume and other primary information for all the geometrical variants.

- A FEA (Finite Element Analysis) tool to define/extract the values of structural and functional requirements (e.g., allowable stress) to evaluate product performances and elaborate the new green variants. First, it is used to check the performance of the original product according to the assigned boundary conditions (loads, constraints, etc.). A set of mechanical characteristics is extracted from this analysis (e.g., the maximum strain and stress), which is decisive in the subsequent configuration of the optimizer. Finally, the FEA tool is used to verify the alternative solutions, obtained after the optimization phase.
- A structural optimization system to set eco-compatibility strategies and generate alternative geometries in combination with different materials and manufacturing processes. Starting from a given design volume and boundary condition data, the structural optimizer permits to obtain, in a fully or partially automated way, the new design solution, which provides the best performance with regard a specific "green" goal and assigned design constraints (e.g. structural and manufacturing).

2. A module, named *Life Cycle Modeling (LCM)*, to map all phases of the life cycle, from pre-manufacturing to the end of use. It is used to mathematically correlate the required mass and energy flows to shape/volume, material and mass of the product.
3. A *LCA-based analysis tool*, precisely eVerdEE developed by ENEA [16,17], which processes the material and energy flows related to a product, and provides as output the indication of its eco-sustainability. This tool is integrated with the LCM module to acquire the previous mentioned data.

Fig. 3 portrays the Eco-OptiCAD framework, where the structural optimizer is the kernel of the system and is used to generate alternative green scenarios of the product according to the triad shape-material-production. The proposed procedure requires five different design inputs to execute the structural optimization strategies and generate the green scenarios as described in the following.

The 3D model of the product under investigation is used both to define the starting geometry of the given product (new or to be improved) and to revise the final alternative solutions obtained in the downstream of the FEA and optimization phases.

The LCA data are a set of environmental impact indicators by which solutions will be evaluated. These data are necessary to perform the life cycle assessment for the given product and, later on, for all the new alternatives created by the proposed eco-design

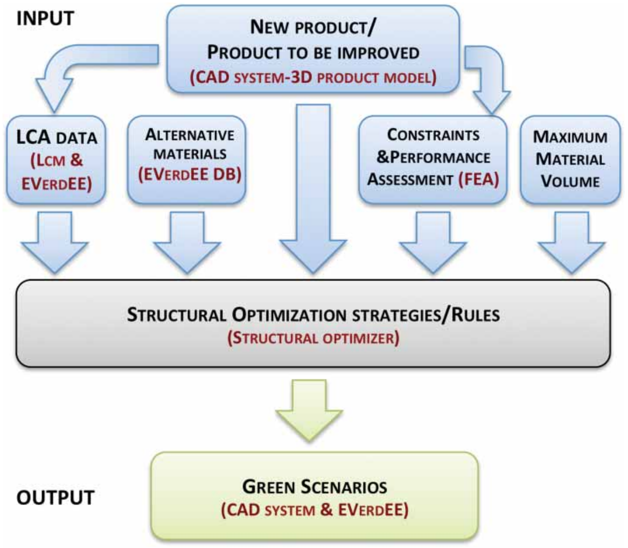


Fig. 3: Eco-OptiCAD framework.

framework. They are essential to identify which is the best direction to be followed by designer in terms of shape, material and production process.

The alternative materials are selected from the database of substances and processes made available by the eVerdEE LCA. It is a library of ecological materials and alternative processes directly available during the design phase. The selection of the material is very critical and affects the amount of raw material required, its manufacturing process, the suitability of recycling, etc. From this point of view, the eVerdEE library allows a rapid and significant estimation of the environmental impact. Materials are represented by a set of properties (mechanical, thermal, electrical, etc.) to configure the FEA tool and the optimizer.

The constraints and performance assessment are derived from FE analysis. In fact, designing by optimization techniques means translating a design task into a mathematical problem with the following basic entities:

- An objective function, i.e., the performance of the system that the designer wants to reach or improve.
- A set of design variables, i.e., the parameters of the system affecting the objective function.
- A set of loading conditions and constraints representing the requirements the system has to satisfy.

Finally, the structural optimizer specifically requires the maximum volume of material from which the new concept of the product has to be derived.

In the following, more details are provided about the LCM module and the optimization strategies that have been specifically developed to fulfill our goal.

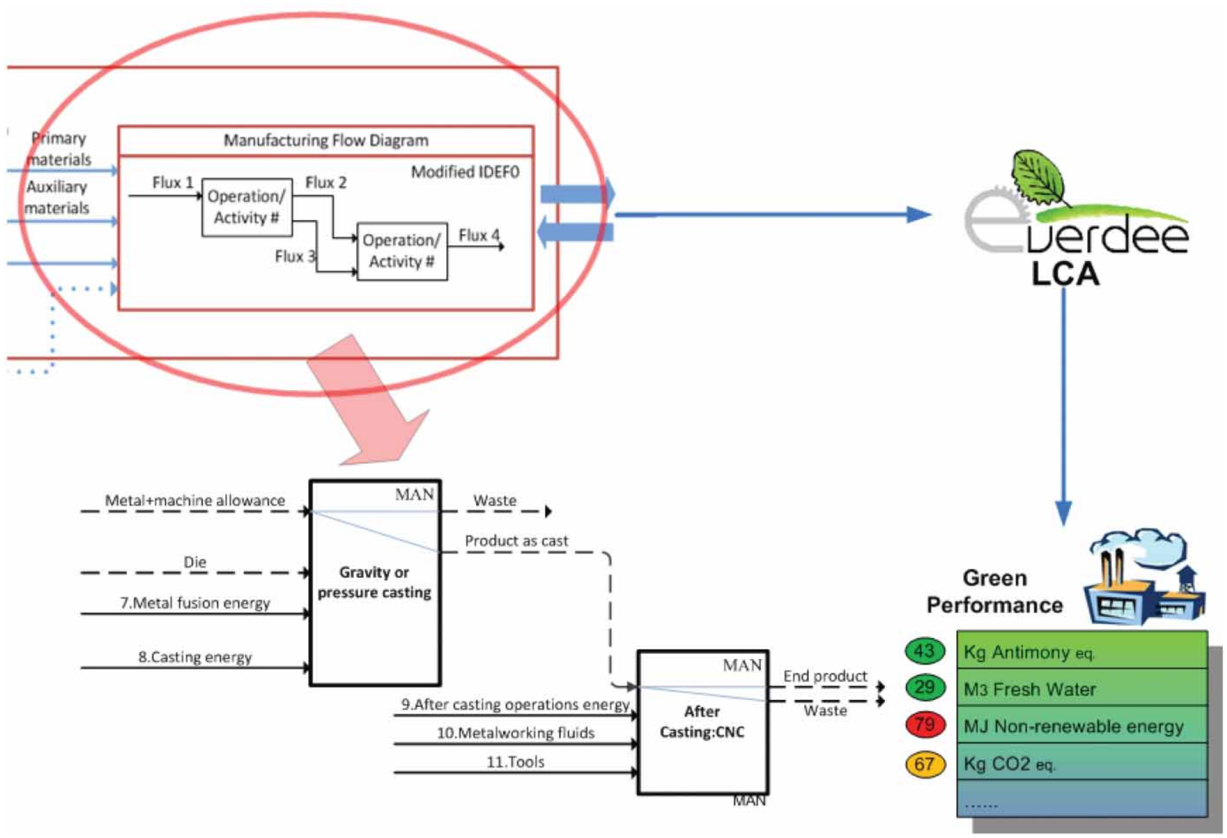


Fig. 4: Life Cycle Modeling and eVerdEE LCA.

4. LCM MODULE

The LCM module has been developed to easily map all phases of the product life cycle, from pre-manufacturing to the end of use. It is interfaced with eVerdEE to get LCA data necessary to evaluate green scenarios that will be generated using the structural optimizer.

Thanks to eVerdEE, the user proceeds to the definition of system boundaries, the assessment of data quality, the selection of impact categories to be monitored, and the entry of material and energy flows. Quantitative data are taken directly from the LCM module and then automatically processed by eVerdEE. Fig. 4 shows the operative schema.

The LCM adopts a modified IDEF0 technique [18] to map the life cycle phases. A phase is schematized as a sequence of activities where materials and energy flows are associated to each of them (Fig. 4). Boxes represent the activities (in Fig. 4 those ones of manufacturing process), dashed arrows materials (from left-side of the box as input to the activity, from right of the box as output of the activity) and solid arrows energy flows. Energy flows primarily depend on the set of the three key parameters: Material, Shape/Volume, Production process (M, S/V, P).

The LCM is used not only to represent each phase in terms of inputs, operations, and outputs, but also to correlate, as much as possible with mathematical relationships, each flow to the optimized model (M, S/V, P). Numerical data are associated with materials and energy flows according to the product under investigation. This is achieved through the use of external information, such as specific literature, datasheets, and best practices (e.g., machining allowance and energy of fusion, the number of trucks, the consumption of fuel associated with the transport) or calculated by means of virtual design software.

We have developed a set of standard manufacturing templates (LCM diagrams) of the main production processes, such as expendable mold casting, permanent mold casting, molding (as an example of processing by plastic deformation) and machining, and collected related data. These templates can be used for different products but numerical data should be updated and related to the specific product. When the user wants to consider a new production process, new models and data about the life cycle product must be collected and/or calculated. This means that different LCM templates have to be developed for different industrial contexts. The inputs of the diagrams correspond directly to the fields of data that must be filled in the LCA module.

Even if the level of detail does not correspond to that of a definitive life cycle, it is sufficient to suggest the designer the best direction for "green" design.

5. OPTIMIZATION STRATEGIES

A structural optimizer is able to autonomously generate the best geometry/shape to reach a given goal, with regard to structural and technological constraints.

The geometrical properties and the mass of a component determine the amount of material to make it, the size of the raw material, the energy and the manufacturing process, the type of packaging, etc. Properly addressing the structural optimization process is therefore possible, still in a CAD/FEM environment, in order to obtain results that, while fulfilling all the structural and functional requirements, are already oriented to the respect of some environmental requirements. Furthermore, the optimization procedure ensures that the best geometry is found to satisfy considered requirements.

We considered the optimization typologies that are the most appropriate to find new concepts and determine important changes in the product from eco-design point of view. In particular, we considered topological optimization and topographic optimization [19]. The former permits to obtain the optimal shape and distribution of material within a defined space (design space) and for a set of load configurations and constraints. The SIMP (Solid Isotropic Material with Penalization) method underlies this optimization typology. The latter is an advanced type of shape optimization. Once the design space is defined, the optimizer creates a pattern of reinforcements of variable shape within that space; the geometry of the product is modified to build local reinforcements, such as ribs, and increase the stiffness. The typical application of this optimization is the creation of patterns of reinforcements for sheet metal structures subjected to various types of load, varying the shape of the sheet, but not its thickness.

The goal of getting products more compact and light, which means theoretically more eco-compatible, can be achieved not only by directly changing the mass or volume of the product, but also minimizing the compliance and/or certain mechanical properties such as maximum stress or strain encountered on the piece in typical load conditions.

In our system, the research of structural optimization strategies oriented to eco-design has been primarily focused on the phases of pre-manufacturing and manufacturing, and secondarily on end-of-use and packaging. Tab. 1 reports the strategies identified for the pre-manufacturing, manufacturing and use phases subdivided according to the considered optimization typologies.

For example, for topological optimization, the strategies are divided into two groups (A and B) whose goal is obtaining a reduction of mass (or volume) while maintaining adequate mechanical characteristics. "A1" strategy aims at getting the volume as low as possible in the design space without exceeding a given maximum allowable value of the stress.

6. EXPERIMENTATION

Eco-OptiCAD has been validated with an industrial case study, a connecting rod. The connecting rod has been chosen because it's a well-known product, optimized for manufacturing process, costs and high performance. Thus, it can be considered a challenging test case for our guidelines that has produced very good results with less complex case studies [20,21].

The inputs for the analysis have been the following:

- LCA of the connecting rod was calculated fixing the functional unit as the annual production of 375,000 four stroke engines, that means 1,5 millions units per year.
- Allowable materials. The given rod was made of steel Ni-Cr-Mo alloy. It could be also made of several metal alloys: carbon steel for low power engines, Cr-V or Cr-Mo steel for high power engines and nitrid Cr-V for very high performance engines. For the sake of brevity, we present in this paper only results generated with one material, steel Ni-Cr-Mo alloy.
- *Constraints & performance*. Forces on the rod are due to gas pressure on cylinder and inertia, while friction forces have been considered negligible. Thus our calculation considered the stem of the rod subjected to traction and compression, and a bending moment due to the inertial forces perpendicular to the axis (with a maximum when the connecting rod is perpendicular to the crank). For constraints, we considered a pin joint at the head and a roller joint at the bottom head.
- *Max material Volume*: It has been considered the maximum volume of the rod during its movement inside the cylinder without any interference with all other mechanical parts. The rod thickness is the same of the given rod. In order to assess data for the following optimization step the maximum material of the given rod has been considered to calculate strain and stresses in the 3 load steps above mentioned (compression load, traction load and lateral inertia). Tab. 2 shows the values calculated for the "A2" strategy where maximum allowable values for deformations are required.

- *Production process*: LCM module has been used to model the whole life cycle of the product, with particular attention to pre-manufacturing and manufacturing. We considered both melting and CNC processing by using the two related LCM maps. Furthermore, manufacturing process has been managed by combining the requirements during the following optimization process. For example, we used "extrusion" and/or "draw direction" constraints for the melting process and the "Maximum member size control" for CNC manufacturing. In the use phase, the kinetic energy of the connecting rod is provided calculating the speed of head and bottom head points and substituting the rod with 2 equivalents masses (m_A and m_B) and a virtual momentum of inertia J_0 as shown in Fig. 5.

Fig. 6 summarizes the input data for the considered case study. Environmental impacts, automatically calculated by using LCM modules, are also shown.

Strategies reported in Tab. 1 have to be applied to the maximum material shape for all material/production process combinations we want to test.

For sake of brevity, the entire analysis has been reduced. Optimizations have been launched considering only Ni-Cr-Mo steel and without changing requirements during optimization process. We used only the

Life-cycle phase	Optimization	Strategy	Goal	Constraints
Pre-manufacturing/ Manufacturing/Use				
	Topological	*A1*	Minimize volume	$\sigma \leq \sigma$ amm
		A2	Minimize volume	*displacements or deformations* $\leq$ *max allowable values*
		B1	Minimize compliance	volume fraction $\leq$ % volume initial desing
		B2	Minimize compliance	*volume* $\leq$ *volume max*
		B3	Minimize weighted compliance	volume fraction $\leq$ % volume initial design
	Topographic	*A*	Minimize stress/strain	*reinforcements geometry constraints*
		B	Minimize compliance	– volume fraction $\leq$ % volume initial design – reinforcements geometry constraints
		C	Minimize maximum stress by *minmax problem*	*reinforcements geometry constraints*
		D (TPG+Size)	Minimize volume	*deformation (or strain) most critical for the model* $\leq$ *max allowable value*
		E (TPG then Size)	**Topographic** Minimize strain (or stress) most critical for the model	**Topographic** *no constraints*
			Size Minimize volume	**Size** deformation (or strain) most critical for the model $\leq$ max allowable value

Tab. 1: Eco-design optimization strategies.

Traction load		Compression load		Lateral Interia load	
ε(mm)	σ(Mpa)	ε(mm)	σ(Mpa)	ε(mm)	σ(Mpa)
0,33	485	0,12	489	0,14	257,3

Tab. 2: Strain and stress values of the starting connecting rod used in the "A2" strategy.

$$V_B = -r\dot{\varphi}[\sin(\varphi) + \frac{r}{2l}\sin(2\varphi)]$$
$$m_A = \frac{b}{l}m_{rod}$$
$$V_A = -r\dot{\varphi}$$
$$m_B = \frac{a}{l}m_{rod}$$
$$J_o = J_{rod} - m_{rod}\,a\,b$$
$$\dot{\gamma} = -\frac{r}{l}\dot{\varphi}\cos(\varphi)$$

$$E_{rod} = \frac{1}{2}m_B V_B^2 + \frac{1}{2}m_A V_A^2 + \frac{1}{2}J_o\dot{\gamma}$$

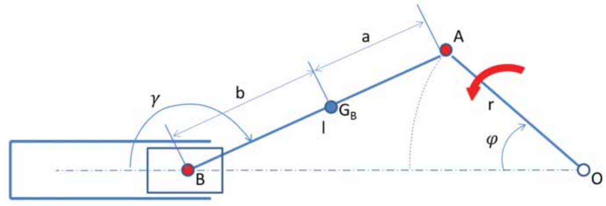
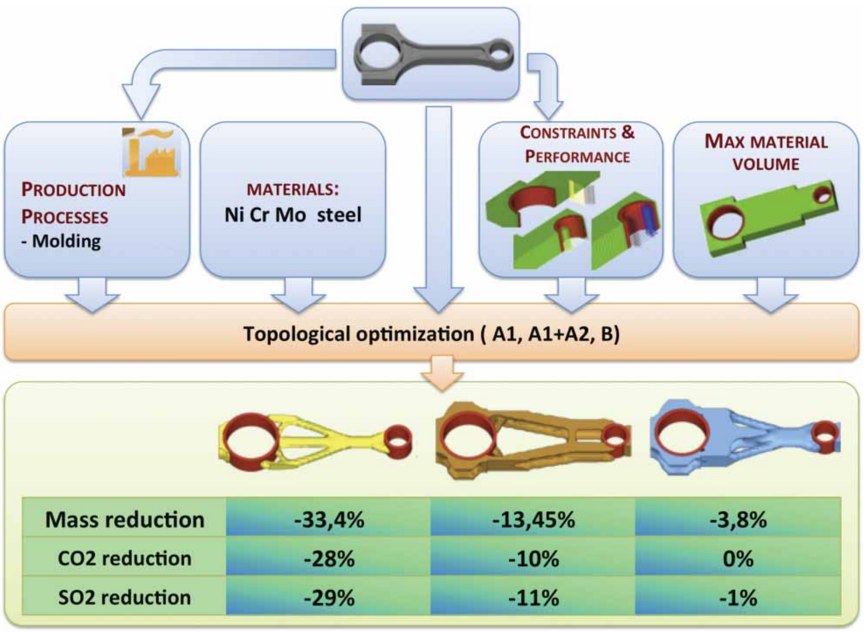


Fig. 5: Schema used to calculate the kinetic energy of the connecting rod.



Mass reduction	-33,4%	-13,45%	-3,8%
CO2 reduction	-28%	-10%	0%
SO2 reduction	-29%	-11%	-1%

Fig. 6: Input data for the connecting rod.

set for molding. Furthermore, we considered a subset of ECO-design topological optimization strategies, precisely A1, A1+A2 and B strategies.

The ultimate result is 3 uncommon shapes for the connecting rod, automatically generated by applying Eco-Design strategies. All satisfy functional requirements and have better environmental indicators. These results are used to support designer's decisions towards a new design, more ecofriendly. Next step consists in moving from the optimization world to the CAD environment and, then, choosing the best product variant. Fig. 7 shows the CAD models corresponding to the 3 solutions. From a "green design" point of view, the best optimization (Fig. 7a) reduces 29% of SO2eq and 28% of CO2eq, i.e. more than 9.000 tons of CO2 equivalent per year.

The case study permitted the authors to verify the feasibility of proposed approach. All solutions meet the design criteria and are better than the given connecting rod with regard to the environmental impact. It is clear that it is quite impossible for the designer to take into account how changing material, shape, or manufacturing process influences its life cycle phases and the final impact on each environmental indicator. Therefore, the proposed method permits to automatically generate inedited and optimized combinations of the triad material-shape-manufacturing process thanks to the adoption of a structural optimization tool properly configured for eco-design. This means that the optimization tool is very helpful since the impact of product modifications is evaluated directly on the entire product life cycle.

The case study also demonstrated that best environmental improvements could be obtained not by changing the product geometry, the material or the manufacturing process, but rather by acting

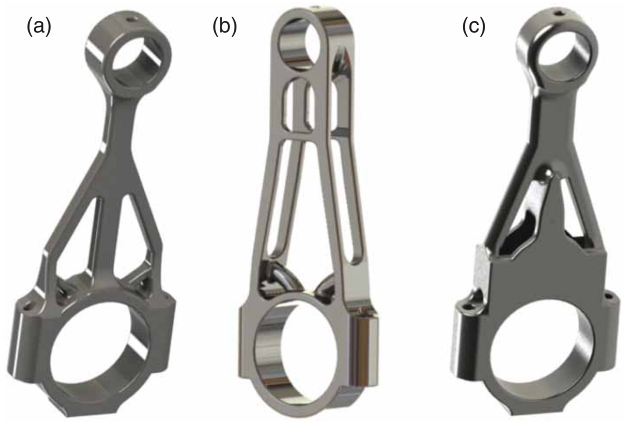


Fig. 7: 3D CAD model of a connecting rod designed by a CAD user.

simultaneously on the combination of these three parameters.

7. CONCLUSIONS

In this paper, we present an eco-design approach and a software framework, namely Eco-OptiCAD, able to support the designer during the environmentally sustainable redesign of any product that can be modeled in a CAD environment. The approach is based on the integration of three tools connected to the CAD environment: CAE, Life Cycle Modeling (LCM) and LCA tools. Therefore, it is possible to generate, automatically, inedited and optimized combinations of material-shape-manufacturing process. This is obtained thanks to the adoption of structural optimization tools properly configured for eco-design.

Once input data are provided, the framework generates product variants in terms of combination of shape/material and manufacturing process. They have not to be considered as the final result but as strategic directions for implementing greener products.

The case study of the connecting rod has been used to explain the efficacy of proposed approach and software environment. It has been demonstrated that, even for consolidated products as the connecting rod, good results in terms of environmental impact indicators can be reached.

At present, the framework is still under development and all different modules are not fully integrated; however, it is completely independent from the specific CAD system used and other structural optimization tools can be easily integrated.

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