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Virtual eco-design: how to use virtual prototyping to develop energy-labelling compliant products

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Abstract

The paper defines a framework called *virtual eco-design* aiming to support designers and engineers in the development of sustainable energy-related products. Virtual prototyping is used to perform energy consumption tests according with ecodesign and energy label regulations. The goal is to build a knowledge-based repository in which virtual tests are stored and classified to create eco-knowledge. Induction hob has been analysed to verify the applicability of the approach and the integration in a traditional product development process. Results highlight how the proposed methodology increases company eco-knowledge providing a tangible support in the definition of energy-label compliant products.

Keywords: eco-design, eco-knowledge; virtual prototyping; energy-related products; energy labelling

1. Introduction

Nowadays, several companies are approaching to environmental matters and they are working to increase the quality and the environmental sustainability of their products. This need is born by the necessity to be compliant to European community directives, whose priority is the development of sustainable products as main drivers for competitiveness and growth [1]. Eco-design is defined as the integration of the environmental aspects into product design and development, with the aim of reducing environmental impacts throughout a product's life cycle [2]. A product, in particular energy-related product, is something with a story: it is born from raw materials, has a use phase and an end-of-life and must be analyzed considering the integration of all environmental aspects throughout its life cycle [3]. It is well-known that a large percentage of life cycle performances are determined by the product design, in particular early design decisions [4]. The approach to sustainability principles has a strategic importance because it helps to prevent negative impacts and to define the overall environmental profile from the design stage, with a view to reconciling environmental matters and economic competitiveness. Eco-design is a vehicle of product innovation for that companies which are involved in the environmental responsibility [5]. However, eco-design is not systematically applied in technical departments due to the gap between available solutions and needs of industrial sectors [6]. Regarding design tools, virtual prototyping (VP) is widely used as computer aided engineering (CAE) systems during the product development process. VP is conceived to "virtualize" the product under development and to analyze physical behaviors of products (mass, materials properties, stress, deformation, etc.) [7]. VP allows to estimate the product performance without going through a physical prototype, but a systematic integration with the eco-design regulations and labelling indicators is still an open issue [8].

The goal of this paper is to define a structured methodology and related tool called *virtual eco-design* (VE). VE framework aims to support designers and engineers in the development of environmental sustainable products, taking into account eco-

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design and energy label regulations since the early phase of product design. The idea underpinning this research work is to integrate principles of eco-design standards (laws, mathematical models, thresholds, etc.) in a virtual environment (model and boundary conditions) creating a robust model for energy consumption tests. In addition, performed tests are used to create internal eco-knowledge which can be spread inside technical departments and used in a definition of new product concepts. Considering the typical design workflow, *virtual eco-design* approach will help the identification of product environmental requirements, together with the estimation of product energy performances excluding the production of physical models and prototypes.

The paper is structured as follow: after a brief description of the state of art on eco-design and product virtualization (§2), the VE framework (method and tool) is proposed including the impact in the traditional product development process (§3). A case study (induction hob) is analyzed by using this framework and the preliminary results are reported (§4). Lastly, discussion (§5) and conclusion are proposed (§6).

2. State of art and research context

Company knowledge is recognized as a crucial element for the survival of industrial organizations and its sharing among different actors of the design process is considered an element for the success of the organization [9]. Environmental sustainability represents a relatively new aspect that companies start to implement in these last decade and for which much of the knowledge still has to be created. If company knowledge represents a key aspect in design, this fact is exacerbated in eco-design, where tools and regulations change rapidly, activities are highly collaborative and interconnected and therefore the sharing of common documents and data could facilitate the design process and the development of sustainable products [10]. The transition toward eco-design involves different levels in the company organization as well as the necessary commitment and resources. Emerging eco-design approaches aim to integrate ecological aspects into business strategy analyzing changes in the organization [11]. A large number of eco-design methods and tools have been developed in the past years [2,8]. Researchers and academic world tried to formalize eco-design principles and methods with the aim to support companies in the design of ecological products. The developed solutions are usually too far from the industrial needs and those tools are scarcely applied within the industrial context [12,13]. The following barriers can be identified: (i) methods complexity [14,15], (ii) involvement of specialized personnel [16], (iii) timing and high resources required [17,18], (iv) lack of concrete guidelines and supporting tools [14,19], (v) hard integration within the product development process [20] (vi) prioritizing in projects and objectives [21]. Therefore, it is necessary to change the means to support designers and make them competitive with specialized expertise and complete capacity to define their skills in the environmental issues of product development. In recent years, literary review shows the increasing relevance of VP in product development, with the employment of modeling and numerical simulation techniques. The virtual prototype of a generic system is a numerical model that contains several information about the product. Rapid use and refinement of computational methods are leading to incredibly fast growth of VP technology, increasing its robustness, accuracy and precision [22]. Currently, a great number of software is involved in VP: 3D CAD systems, finite element analysis (FEA) and computational fluid-dynamic (CFD) tools [23,24,25]. However, VP has been used only with limited extent in eco-design [26]. Firstly, VP does not allow to directly assess environmental performances even results of VP can be handled for the inventory phase of lifecycle analysis. Secondly, simulations of different product configurations are not used to compare two alternatives from the environmental perspective. A possible solution to promote environmental awareness is the development of a comprehensive framework for product development that combines the existing design tools such as VP and the requirements of eco-design and energy labelling standards.

3. VE framework

In this section, the VE framework is presented. Firstly, the approach is proposed describing the activities to perform and the tools used and developed. Secondly, the interaction of this framework within the traditional product design context is shown, including the relative achievable benefits in the development of energy-related products and their compliance with the energy labelling standards.

3.1. VE approach

VE approach has been conceived to assist engineers in ecological design choices thanks to the consultation of an eco-knowledge collected in a structured database that integrates contents related to eco-design and virtual prototyping (e.g. eco-design guidelines and regulations, product information, test cases, virtual prototyping studies, etc.). VE framework is proposed in Fig. 1 and main aspects developed in this approach are reported here below.

3.1.1. Creation of a virtual model (one for each mechatronic product) which simulates energy and environmental performances in compliance with ecodesign standard

The virtual prototyping is a numerical simulation of a virtual product model that can be analyzed and tested from different aspects (design, engineering, performances, manufacturing, configurations parameters, behavior, etc.). Product virtualization allows to evaluate possible design solutions (such as shapes, dimensions, materials, etc.) and to assess through the virtualization of energy label test their influence on energy consumption. Simplified procedure needs to be developed with the aim to virtualize the energy label tests and to achieve robust results. Simplified CAD geometry of the system is required in order to include each level of product structure since the design process. FEA and CFD tools have been used to investigate the effective solutions of analysis problems in complex structures. FEA and CFD models gives insight and provides detailed analysis of operating conditions in lieu of difficult, intrusive, and often expensive experimental methods and configurations.

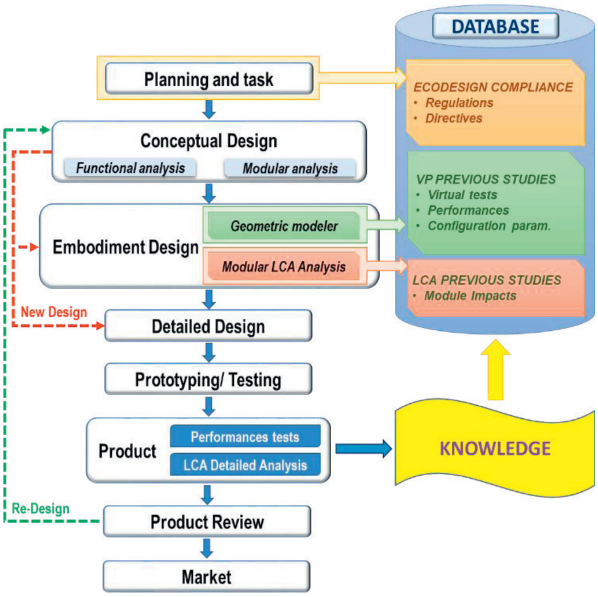

Fig. 1. VE framework

3.1.2. Development of a structured repository to collect and efficiently share information

The core of the methodology and tool is represented by its database, in which eco-design guidelines, virtual prototyping studies and life cycle analysis are stored and organized in order to facilitate their consultation. VE database allows to collect all information about product design and redesign. The database is structured in two different levels: (i) as a repository of virtual analyses in different product configurations (materials, dimensions, etc.) and (ii) as design tool to support decision-making process oriented to eco-design (design rules and guidelines based on the knowledge acquired by virtual analyses and literature). Virtual analyses and simulations derived from FEM and CFD analytical solvers and they are performed in compliance with energy label tests. VE database is filled every time a new virtual simulation is performed and with LCA results of new product modules. This information can be stored in the database section and reused by designers the environmental evaluation of product modules/components during the design phase.

3.1.3. Creation of a company knowledge that collects all the information in order to have valid guidelines for the development of new design concepts.

VE approach permits to create a company knowledge that can be shared among the designers and engineers inside a manufacturing company. The knowledge can be constituted by all past choices made by designers during the design process, choices related to product/process data and simulations (materials, dimensions, strategies, etc.). In particular, knowledge is creating starting to each specific product module and its impact on the overall product performances. This information is managed by the same product engineers to define specific design rules and guidelines. These latter are stored in structured way in the knowledge database and reused during their design activities. In this way, designers and engineers can know the correlation between design choices and their environmental impacts and eventually they can rapidly modify the component or the product. This methodology allows reusing eco-knowledge information for the development of new product or for product re-design.

3.2. Integration of the virtual eco-design method within traditional design process

Product development is a consolidated and standardized process in industries [27]. This design process is followed whenever it is necessary to design a new product or to re-design a particular one with the aim to improve some specific characteristics. Design phases have a precise meaning and specific role in the overall process. With the aim of an efficient integration of VE within traditional design process, the following steps are modified based on the proposed framework (Fig. 1) and described here below.

Planning and Task. In the first step of product development process, a list of requirements considering specific needs for the product under analysis (performances and environmental considerations have to be considered) is defined. For example, consultation of eco-design guidelines from VE database allows designers to acquire necessary know-how on specific product requirements in terms of energy performances and environmental impacts. All these general suggestions coming from mandatory regulations, legislations and standards are associated to a specific product.

Conceptual Design. In the second step, designers study general solutions to reach the tasks defined in the first phase. The result of this step is the generation of product architecture (modules) based on the functional analysis [27]. The product is broken down in different modules/components with specific functions. During this step, only "high level" information are available by the consultation of VE database (e.g. the most efficient solution for common modules such as "lights", "electric motors", etc.). So doing, designers can configure the product architecture combining "high level" eco-design suggestions and other traditional recommendation (e.g. costs).

Embodiment Design. The third step is characterized by the definition of the overall layout design and the identification of the main features of the products. This phase is supported by the use of traditional design tools such as CAD systems. In this step designers can consult all company knowledge about eco-design, performances and virtual tests. In particular, this knowledge is collected in the VE database and is represented by: (i) results of environmental sustainability analysis, (ii) results of energy label virtual tests, (iii) past design choices to re-apply for solving problems and to improve the environmental impact of product, etc. The knowledge can include company internal specifications, normative and rules related to environmental sustainability that designers have to respect. By consulting the database, designers are supported in the definition of new possible product improvement strategies. This phase enables designers to identify also the main environmental impacts of product, through a simplified module for the calculation of environmental impact. In this phase, a modular LCA analysis of the product are carried out to understand the environmental consequences of specific choices and quantify the possibility to further improve product environmental performances. In this way, the product will respect not only the technical and economic requirements, but also the environmental ones. A specific section of VE database store the environmental impacts (score) of the developed module/component. So doing, a preliminary idea about environmental impact of different product configurations are provided. VE database shares the knowledge in an easy way. The shared eco-knowledge can be used at different level in the company organization.

Detailed Design. In this step, product components are drawn for production considering the all mentioned aspects.

Prototyping/Testing. In this step, the product is prototyped and experimental tests are carried out to verify the requirements established during the workflow.

Product. If initial requirements (planning and task) are satisfied, final product configuration is frozen and available for production/manufacturing. The defined configuration will be part of the eco-knowledge stored in the VE database. If requirements are not satisfied, product review is necessary.

Product review. Whenever is necessary, some modifications to the final configuration can be done to reach the objective fixed in the beginning of the project. In this case, designers come back through the approach starting from new design concepts (re-design).

During the implementation of this methodology, designers can acquire knowledge on eco-design, sustainability and product performances, thus increasing their competences on this topic. So doing, company eco-knowledge will grow and will become the most important source of information to support design choices.

4. Case Study

VE approach has been preliminary applied to an induction hob which is a mechatronic product subjected to Eco-design directive [1]. This latter provides a clear framework about the sustainable design of products and it has been extended in 2009 to all energy-related products, or products with an impact on energy consumption during the use including ovens, hobs and kitchen hoods (EU No 66/2014). In particular, the European standard EN 60350-2 regulates the measurement of energy consumption of induction hobs.

4.1. Energy consumption test

The energy consumption measurement of induction hobs is representative of an actual cooking process, during which, to a first heating phase, follows boiling. Energy consumption test satisfies the repeatability and reproducibility requirements. Test is carried out at room temperature (20° ± 5° [C]) and it follows three steps: (i) preheating period, (ii) modulation period and, (iii) simmering period (see Fig. 2). During preheating, the hob is switched on at the maximum power until the water reaches a temperature of 70° [C]. At this point, power is reduced to 25% ± 5% of maximum and the water temperature still continues to rise until it reaches the temperature of 90° [C] (modulation). Simmering starts when water reaches for the first time the temperature of 90° [C] and lasts 20 min in order to obtain a temperature ≥ 90° [C], but near as possible to 90° [C].

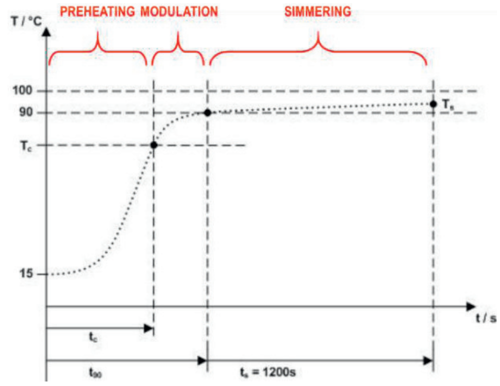

Fig. 2. Energy efficiency test for Induction hob (EN 60350-2)

Pots used during the tests are standardized as well (EN 10088-2) and they are filled in advance of the quantity of water according to their diameter. The water temperature should be (15° ± 5° [C]). The energy consumption for a hob is calculated as follow.

$$E_{hob} = \frac{1000g}{n_{cw}} \times \sum_{cw=1}^{n_{cw}} \left(\frac{E_{cw}}{m_{cw}}\right)$$

Where: E_{hob} is the energy consumption of a hob calculated per 1000g in [Wh], E_{cw} is the energy consumption with a single cookware under test, in [Wh], m_{cw} is the quantity of water used for the test of the cookware pieces in [g] and n_{cw} is the number of cookware pieces on the hob. The result of each cookware is normalized to 1000 [g] of water; the energy consumption is divided by the quantity of water used for the cookware under test and the average of the normalized energy consumption of the hob is calculated considering all cookware pieces under test. The energy efficiency of products covered by this regulation should be regulated by specific parameters which are calculated using reliable measure methods. It is important to follow a standard test procedure when evaluating efficient products so that their performance can be compared with other devices in an unbiased way.

4.2. Virtual Model Development

The multi-physics virtual model is composed by a virtual analysis of the electromagnetic phenomenal and of thermal aspects. The electromagnetic simulations allow to estimate the value of the power produced on the bottom of the pot, while the thermal fluid dynamic simulations investigate the heat exchange and distribution. FEM and CFD tools (Ansys workbench) are coupled to solve simultaneously the electromagnetic and the thermal fluid dynamic behavior of the product analyzed. At this point, the simulation steps, which regards the energy consumption test, are described in accordance with the normative. The structure of the virtual model is represented in Fig. 3

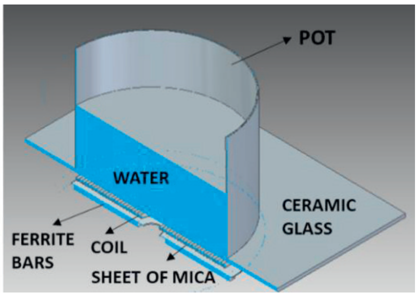

Fig. 3. Virtual model representation (section) of the test system

The system comprises: (i) the pot, (ii) a cooking surface realized in glass ceramic material, (iii) a layer of electric insulation material consisting in a sheet of mica, (iv) an inductor coil to generate the magnetic field, (v) a flux conveyor consisting in several ferrite bars (these latter are disposed radially and equidistant with the aim to reduce the dispersion of the magnetic field), and (vii) water. The approach begins with the virtual analysis of the electromagnetic phenomenon which allows to estimate the value of the current density and ohmic loss produced on the pot, as presented in in Fig. 4.

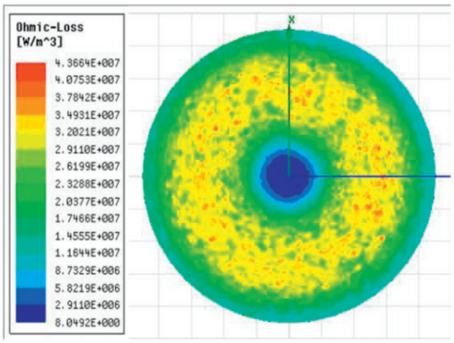

Fig. 4. Ohmic losses [W/m^3] on the bottom of the pot

Fig. 5 represents the section of the model during a thermal simulation step.

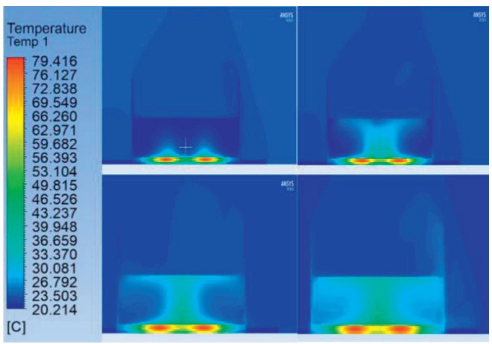

Fig. 5. Heat transfer at the bottom of the pot

It is possible to observe the heat transmission from the modelled system to the water with its interactions to the external environment and the thermal convection of the air surrounding the disk. Results of the proposed system have been compared with experimental tests to validate the virtual model and to estimate its accuracy. Experimental tests have been carried out following the standard procedure and monitoring the water temperature by using a thermocouple positioned at a distance of 15 [mm] from the internal bottom of the pot (EN 60350-2). Fig. 6 shows the comparison of water temperatures between real values and simulated ones.

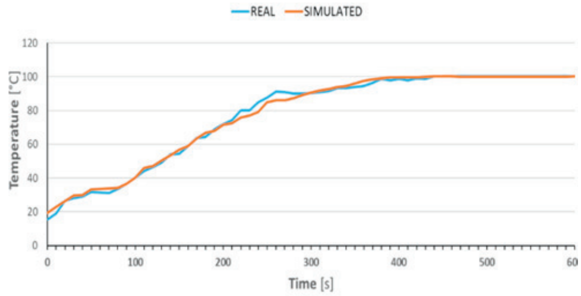

Fig. 6. Water temperature comparison: real (blue) vs. simulated (orange).

As reported in the graph the maximum error estimated by using the virtual model is around 4% and it can be considered acceptable for this kind of analysis. After the assessment of the error between the real test and the virtual one, the virtual model can has been parametrized with a set of all involved parameters grouped by type: geometry, physics and operational phase. The geometrical parameters are all dimensions related to element of the system, the physical parameters are the properties of the involved material and the parameters about the operational phase regard the setting of values such as frequency, voltage, current, set point conditions (time and temperature), etc. Each parameter can be defined and described by an initial value, a range of possible variations, a type, and a unit of measure. The parametric virtual model can reproduce the electromagnetic and thermal behaviour of product studying different configurations and can support the analysis of their energy performances in order to optimize the product. All these virtual simulations are currently under analysis. Obtained results are stored time after time in VE database. Preliminary investigation about obtained results highlights how the most influencing parameters in the environmental performance (both energy consumption test and LCA) are: (i) coils material, (ii) coils dimensions and, (iii) coils geometry. This eco-knowledge are currently formalizing among company engineers and designers and it will be used to define specific rules and guidelines.

5. Discussion

From the state of art analysis emerges that the academic research provides detailed methodologies often too complicated to be applied in daily industrial activities [29,30,31]. Transition toward eco-design practices in industries looks complicated due to a lack of eco-knowledge of product especially in the early stages of process design when design freedom is high [32,33]. The possibility to consult eco-knowledge and eco-design guidelines during the design process allows to implement design strategies oriented to sustainability and energy efficiency. In particular, the VE approach provides a tangible support in the decision making process evaluating the effect of design choices in the final assessment of energy consumption tests. This is the main goal of VE approach and it seems beneficial for the development of eco-knowledge and environmental awareness inside a company compared with other approaches (e.g. people training, use of dedicated tools, etc.) [34]. In addition, VE approach can be easily implement within the tradition workflow of product development and using existing design tools and suites.

6. Conclusions

VE approach has been developed to account environmental issues in the early phase of product development process. The coherence of VE assume a very important relevance thanks to its consolidation upstream of the design process and downstream in the product and product review phase. The tool and the consultation of the database leads to the collection of eco-knowledge on energy-related products subjected to eco-design and energy labelling directives. VE database is structured in order to collet eco-knowledge from literature and guidelines derived from virtual analysis (virtual prototyping). In this way, designers can increase their knowledge on environmental sustainability. By a structured eco knowledge, companies can embody it in products and can innovate its role and gaining competitive advantage in the sustainable matters. Companies can improve their skills and expertise in the design process oriented to the environmental sustainability and create a sort of knowledge-based database which will enhance the eco-design sensibility to the environmental question.

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